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REFERENCE MEASURING METHODS

Specification Guidelines

Version 1.1

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SONY PHILIPS

Compact Disc

REFERENCE MEASURING METHODS

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Philips Intellectual Property & Standards
Business Support
Building WAH-2
P.O. Box 220
5600 AE Eindhoven
The Netherlands

Fax.: +31–40–2732113
Internet: http://www.licensing.philips.com
E-mail: info.licensing@philips.com

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1 Introduction

The intention of the CD-standard (Red Book / IEC 908) is to specify only the parameters of the CD disc and not the CD playback equipment.
The pit geometry on the disc however, can only be specified indirectly by the HF and push-pull signals. These signals can only be measured by using the optical read-out part of a player. Since the characteristics of this Optical Pick-up Unit (OPU) have a significant influence on the read-out signals of the disc, this player part had to be specified in the Red Book (wavelength, Numerical Aperture, polarization and intensity distribution).
For nearly all other parameters no conditions for the player are specified.
The way in which a player is designed is left up to the player manufacturer. This means however, that in practice big differences between different players are found with respect to several aspects such as: track following ability, playability and audio quality.

CD disc manufacturers are experiencing problems in checking the quality of their discs, because a disc can give good measurement results on one player, while tested on an other player, several parameters can be outside the manufacturer's production process control limits or even outside the limits as specified in the CD standard.
Therefore there is an increasing need for a so-called reference player. This should be a player according to a generally-accepted specification, which uses prescribed measuring methods and is calibrated in such a way that discs, when tested on different reference players, will give the same measurement results.
Such a player may be called a "**CD REFERENCE MEASURING SYSTEM (CD-RMS)**".

This document defines the most important technical parameters influencing the measurement results of CD Parameters. It specifies the characteristics of the basic player components and the measuring methods that should be applied. In this way a reasonable basic accuracy of the measuring set-up can be guaranteed.
Which measurements are included in a CD-RMS is left up to the manufacturer of the equipment, however a measuring player may only be called "CD-RMS" if the applied components and measuring methods are according to this document.
To bring the accuracy, repeatability and reproducibility on the high level, needed to make it a reference system, a set of calibration discs will be made available. With the help of these discs the manufacturers and end-users of CD-RMSs should be able to calibrate their players in such away, that they all give the same measuring results.
This document will not specify the (human) interfaces of the system. This should be dealt with by the equipment manufacturers.
The purpose of this document is to avoid player type dependent influences, as well as to make the measured values influenced by as few as possible parameters.
In the design of a CD-RMS, special attention should be given to the repeatability of the measurements of a disc on one player, where, between the measurements, the disc has to be taken out and put back again in the system. Also the measurements' reproducibility, when measuring the same disc on several different players, should be well taken care of.

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1.1 Definitions

Accuracy	:	The precision of measured values of any disc relative to the values determined by Philips for that disc (e.g. the calibration disc values).
Average (AVG)	:	The average of parameter x is represented as AVG(x).
BER	:	**B**it **E**rror **R**ate: expressed as the average ratio of the number of erroneous bits and the total number of processed bits.
BERL	:	**B**urst **ER**ror **L**ength: the number of consecutive erroneous frames with a specified number of errors.
BLER	:	**BL**ock **E**rror **R**ate: expressed as the number of blocks (= EFM frames) with at least 1 error, against the total number of blocks processed.
CIRC	:	**C**ross **I**nterleaved **R**eed-Solomon **C**ode: the special code used for correcting errors in CD.
CLV	:	**C**onstant **L**inear **V**elocity is the speed with which the recorded pits (or marks) and lands on the disc pass the laser spot in tangential direction.
Data Skew	:	The time difference between the A-time from the subcode Q-channel and the CD-ROM header address.
Deviation (DEV)	:	The deviation of parameter x is defined as the difference between the instantaneous value and the average value of x: DEV(x) = x - AVG(x)
Eccentricity (Ecc)	:	Eccentricity is the offset of the center hole of the disc relative to the center of a circular track on that disc. Sometimes the term eccentricity is used where radial deviation is meant.
ECC	:	**E**rror **C**orrection **C**ode: redundant information, according to some special algorithm, used to correct erroneous bytes.
ECMA	:	**E**uropean **C**omputer **M**anufacturers **A**ssociation. ECMA has close working relations with European and global international standardization bodies like IEC and ISO.
EDC	:	**E**rror **D**etection **C**ode: a checksum over the bytes in a sector or frame. This enables decoders to conclude immediately that an error has occurred during the reading of the information. With the use of ECC, errors of this kind can be corrected to a certain extent. EDCs are applied for instance in the CD Subcode and in the CD-ROM data sectors.
Effect length	:	The average length of a specific (I_3 .. I_{11}) pit or land, as measured by Time Interval Analysis.
EFM	:	**E**ight to **F**ourteen **M**odulation. A method of modulation of 8 bits into sequences of 14 bits. These groups of 14 bits are "linked together" by 3 merging bits.
EFM frame	:	A group of 588 channel bits, representing an EFM sync pattern, one byte of subcode information, 24 bytes of user data and 8 bytes of CIRC error correction parity symbols (see Red Book). The duration at nominal speed equals about 136 μsec.
EFM signal	:	The digitalized (EFM) signal after the EFM slicer.
HF signal	:	The analog (EFM) signal before the EFM slicer.

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IEC	:	**I**nternational **E**lectrotechnical **C**ommission. See also ISO.
ISI	:	**I**nter **S**ymbol **I**nterference: due to the finite dimensions of the focused read-out spot, the detector not only detects the instantaneous pit or land but also receives signals from the previous and next pits or lands.
ISO	:	**I**nternational **S**tandardization **O**rganization. The ISO together with the IEC forms a system for world-wide standardization as a whole.
Land	:	Land is characterized in the following way: When radial signals are concerned, land is defined as the area between the grooves. When HF signals are concerned, land is defined as the area between the pits in tangential direction.
MTF	:	**M**odulation **T**ransfer **F**unction: due to the finite dimensions of the focused read-out spot, the amplitude of the detector signal is depending on the density of the pits and lands, resulting in decreasing amplitudes at higher frequencies. This is called the MTF.
NA	:	**N**umerical **A**perture: a measure for the power of a lens, combining the diameter and the focal distance.
Nominal CD Speed	:	The CLV (scanning velocity) that will result in an average EFM bitclock frequency of 4.3218 MHZ or in an average pre-groove wobble frequency of 22.05 kHz.
Nx CD speed	:	A CLV speed, which is N times the Nominal CD Speed.
OPU	:	**O**ptical **P**ick-up **U**nit: the part of a CD-Player that generates a focused light spot on the disc and detects the signals from the reflected light.
Pits	:	Mastered I_3 .. I_{11} effects.
Playability	:	The ability of a player to play discs with non-optimum signals or defects.
PLL	:	**P**hase **L**ocked **L**oop: a system to regenerate a bit clock.
Polarization	:	Light is an Electro-Magnetic wave with an electrical and a magnetic component. The orientation of these 2 components determine the polarization.
Radial deviations	:	Deviations of a track from its nominal radial position relative to the center hole, measured over one revolution. Radial deviations include eccentricity and unroundness .
Random EFM	:	Random EFM data are characterized by: - In the main channel: random data symbols (e.g. a recorded white noise audio signal). - In the subcode channel: normal subcode information.
Reference Plane	:	An ideal flat plane, determined by the surface of the turn-table on which the disc is clamped during play-back.
Repeatability	:	The precision of measured values of one disc, when repeatedly measured on the same tester.
Reproducibility	:	The precision of measured values of one disc, when measured on different testers.
RIN	:	**R**elative **I**ntensity **N**oise, a figure to express the noise characteristics of the laser diode.

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Subcode	:	Information (track, time, text, graphical or MIDI) stored together with the main channel data on a CD. The Subcode is spread across 8 channels (PQRSTUVW). P and Q contain the track and time information shown on the display of an audio CD player. R..W may contain information defined by special applications, like for instance: CD-Graphics, CD-Text or MIDI.
Sync	:	A special bit pattern, with the help of which decoders can synchronize to a bit stream.
TOC	:	**T**able **O**f **C**ontents: in the Lead-in Area the subcode Q-channel contains information about the Tracks on the disc.
Track pitch	:	The average distance in radial direction between 2 consecutive centers of the spiral track.
Unroundness	:	The deviations of a track relative to an ideal circle with a radius equal to the average radius of the track over one revolution. Sometimes the term unroundness is used where radial deviation is meant.
Variation (VAR)	:	The variation of parameter x is defined as the ratio of the deviation of x and the average value of x: VAR(x) = DEV(x) / AVG(x)
Vertical deviations	:	Deviations of the reflective information layer from the Reference Plane.

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1.2 References

The System Descriptions that are referred to in this document, can be found in the following documents:

- CD-DA : Compact Disc Digital Audio,
  specified in the System Description Compact Disc Digital Audio ("Red Book"), N.V. Philips and Sony Corporation.
- CD-ROM : Compact Disc Read Only Memory,
  specified in the System Description Compact Disc Read Only Memory ("Yellow Book"), N.V. Philips and Sony Corporation.
- CD-i : Compact Disc Interactive,
  specified in the CD-i Full Functional Specification ("Green Book"), N.V. Philips and Sony Corporation.
- CD-ROM XA : Compact Disc Read Only Memory eXtended Architecture,
  specified in the System Description CD-ROM XA, N.V. Philips and Sony Corporation.
- CD-WO : Compact Disc Write Once: name changed to CD-R.
- CD-R : Compact Disc Recordable,
  specified in the System Description Recordable Compact Disc Systems, part II: CD-R ("Orange Book"), N.V. Philips and Sony Corporation.
- CD-RW : Compact Disc ReWritable,
  specified in the System Description Recordable Compact Disc Systems, part III: CD-RW ("Orange Book"), N.V. Philips and Sony Corporation.
- Multisession CD : Multisession Compact Disc,
  specified in the Multisession Compact Disc Specification, N.V. Philips and Sony Corporation.

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2 Overview of CD disc specifications and items that could be measured

The disc formats that could be considered to be measurable on a CD Reference Measuring System (CD-RMS) are the following:

Pre-recorded CD-types: CD Audio, CD-ROM, CD-ROM XA,
CD-i, CD-i Bridge,
Photo CD, Karaoke CD, Video CD,
CD EXTRA (Enhanced Music CD)

Recordable CD-types: (not fully included in this version of this document)
Recorded CD-R (Orange Book part II),
Recorded CD-RW (Orange Book part III)

For a detailed overview of the mechanical, optical and electrical parameters, the following paragraphs refer to the Red Book as well as the IEC 908 document. The ordering of the subjects is the same as in the Red Book.

2.1 Disc Geometry

The DISC GEOMETRY part mainly contains the mechanical parameters of the disc. They can be measured on general geometrical measuring equipment.

2.1.1 Optical requirements

The optical parameters, like substrate thickness, refractive index and birefringence, can be measured on special optical test devices. The reflectivity of the disc could be measured on a CD-RMS indirectly by means of I_{top}, calibrated with a reference disc. It should be noticed however, that I_{top} is not only depending on the reflectivity of the disc, but also on several other parameters, like e.g. thickness variations, disc skew and birefringence.

2.2 Recorded area

The RECORDED AREA parameters can be measured on a CD-RMS, when the player is equipped with an accurate position detector on, or coupled to, the radial tracking device.
Track pitch and linear velocity can be calculated from the number of revolutions and the radial displacement during a certain time period.
It is however difficult to measure momentary velocity variations. What can be determined is the variation of the average velocity as a function of the radius.

2.2.1 Vertical deviations

The dynamic VERTICAL DEVIATIONS can be determined with a vertical position detector on the objective lens and/or from the signals in the focus servo.

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2.2.2 Radial deviations

The dynamic RADIAL DEVIATIONS can be determined with a radial position detector on the objective lens and/or from the signals in the radial servo.

2.3 HF signal parameters

The HF SIGNAL parameters, such as modulation and asymmetry are to be measured on the HF output signal of the pre-amplifier (= analog EFM).

2.3.1 Average Block Error Rate

The BLock Error Rate (BLER) is derived from the results of the CIRC error corrector. Since the analogue processing of the HF signal, before digitalization and bit clock regeneration, has much influence on the BLER, this processing part is completely specified. Also the characteristics of the EFM bitclock regenerating PLL are specified.
Although the BLER is specified as an average over any 10 seconds, it is common practice to measure the BLER over 1 second periods. This method gives a better resolution for peaks in the BLER, however good reproducibility of the results is more difficult to reach. Therefore the accuracy or reproducibility is only specified for averaged measurements over periods of 10 seconds.

2.3.2 Effect Length & Jitter

A parameter added later to the CD-standard is the LENGTH DISTRIBUTION of the pits and lands (the space between pits). In the past the run-length distribution on CD's did not give rise to serious problems. However due to several reasons, the process margins during the production of discs are consumed and more discs appear on the market reaching the limits of certain specification points.
Especially discs with long playing times can give problems. In this case the linear velocity reaches its lower limit, which means that the pits and lands become shorter (higher density). Therefore the pits and lands representing the higher EFM frequencies (I_3) are closer to the optical cut-off frequency, resulting in smaller amplitudes in the read-out signal.
If, in addition to the small amplitudes, the pit/land lengths show deviations (e.g. asymmetry) and variations (e.g. jitter), discs can cause playability problems, in particular on players with less margins.

In the HF signal, the run-lengths represented by the pits and lands on the disc, have discrete values, determined by the EFM modulation. The nominal RUN-LENGTH of pits and lands are: 3T, 4T, 5T, ... , 11T, where T = 1 / $f_{EFM\text{-}clock}$ = 1 / 4.3218 MHz = 231 nsec.

The actual long-term average length of a pit or land of run-length nT is called the EFFECT LENGTH.
The difference between the momentary length and the long-term average length of a pit or land of run-length nT is called the JITTER.

The EFFECT LENGTH and the JITTER have to be measured relative to a calibrated test disc (Philips “Test Sample 5B.x” or the “Multi-point Calibration Disc Set”). See C.8 for an example.

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2.4 Track following

The TRACK FOLLOWING SIGNAL as it is specified in the Red Book, can only be measured in a player with push-pull detection optics.
As with the velocity, it is also difficult to measure momentary variations in the push-pull signal. What can be determined is the variation of the average push-pull signal over 1 revolution, and as a function of the radius.
The push-pull signal has to be calibrated with test disc 5B.x or the Multi-point Calibration Disc Set from Philips.

2.5 Attachments

In the ATTACHMENTS of the Red Book some more parameters and further clarifications have been given.

2.6 Options

As options on a CD-RMS, format checks on the DECODED SIGNALS can be carried out for the subcode information and CD-ROM data contents of a disc.

The following figure shows how a CD signal can be broken down into several levels for analyses.

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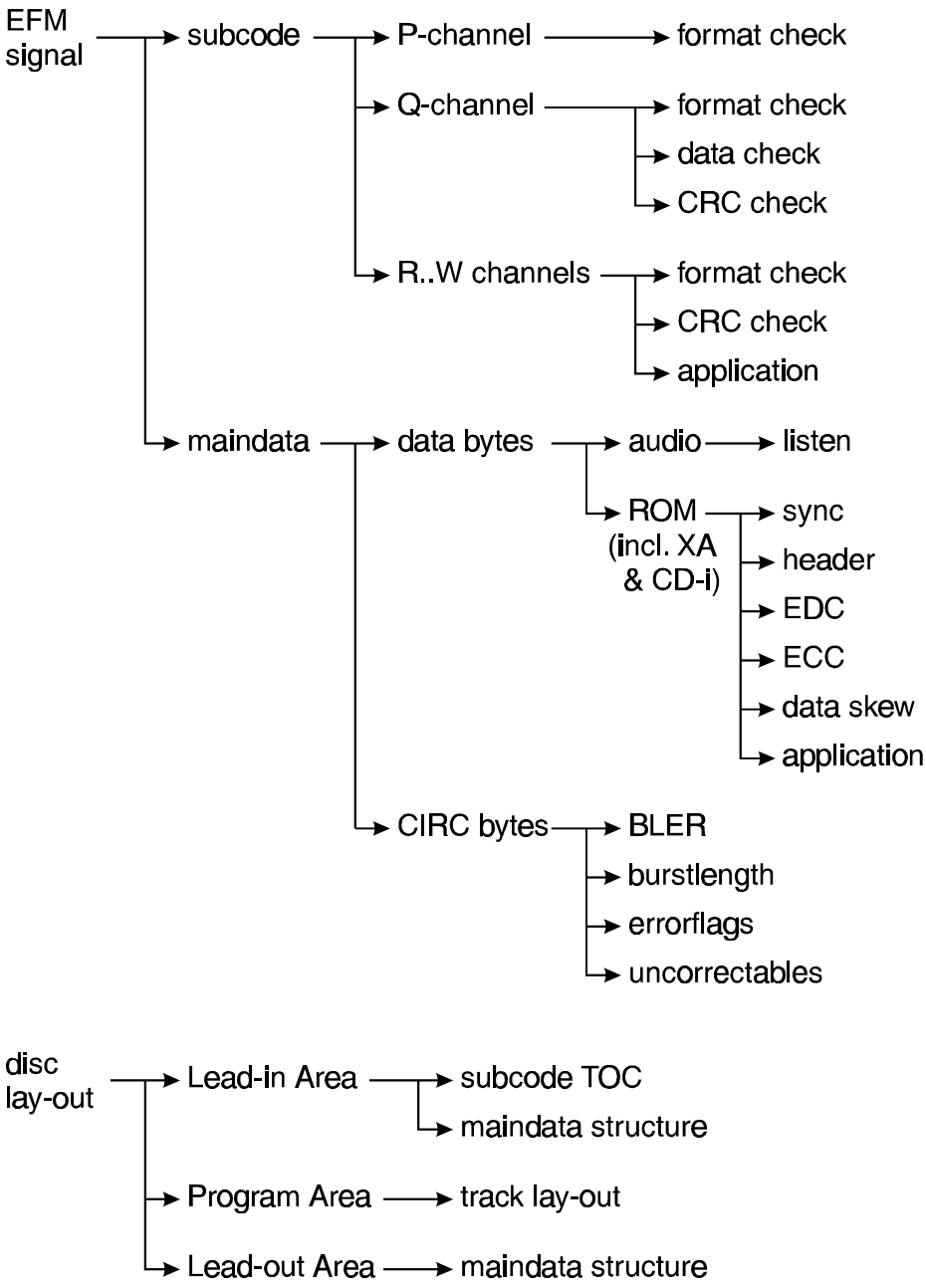

Figure 1 Break-down of signals

3 Parameter specifications and their required accuracy

In this section, an overview is given of the parameters which could be measured by a CD-RMS. A connection has been made to the values as specified in the Red Book. Also the measuring range and the basic accuracy of the measuring equipment is given.
The measuring range of the equipment shall be sufficiently linear (or shall be compensated for non-linearities). Parameter values outside the measuring range shall not give rise to results that could be interpreted as valid values.
For most of the parameters the accuracy is specified as a maximum absolute error of the measured value. The given accuracies are meant as target values, which CD-RMS system designers should aim at.
For some parameters the accuracy is specified as a combination of a maximum relative error + a maximum absolute error of the measured value. In this case the first value of the accuracy definition specifies the relative error as a percentage of the measured value and the second value specifies the absolute error as a fixed value: $\pm$ x% $\pm$ y units.
An example of this accuracy specification is given in Annex B.

The final accuracy of the results shall be further increased by calibrating the CD-RMS with reference discs, which contain signals with specified values for certain parameters.

In specifying accuracy, one could differentiate in the following ways:

Accuracy : the precision of measured values of any disc, relative to the values determined by Philips for that disc (e.g. the calibration disc values).

Repeatability : the precision of measured values of one disc, relative to the values when repeatedly measured on the same tester.

Reproducibility : the precision of measured values of one disc, relative to the values when measured on different testers.

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3.1 Recorded area

RECORDED AREA			target values for:		
parameter	abbre-viation	Red Book specification	measuring range	measuring accuracy	remarks
Start diameter Lead-in	SDL	≤ 46 mm	44 ~ 118 mm for diameter measurements	± 20 µm *	at 23 ± 2 °C & 50 ± 5 %RH
Start diameter program	SDP	$50^{+0/-0.4}$ mm		± 20 µm *	
End diameter program	EDP	≤ 116 mm		± 20 µm *	
End diameter Lead-out	EDL	≥ EDP + 1 mm		± 20 µm *	
Track pitch	TP	$1.6^{\pm 0.1}$ µm	1.4 ~ 1.8 µm	± 10 nm	
Scanning velocity	SV	1.20 ~ 1.40 m/s	1.15 ~ 1.45 m/s	± 0.005 m/s	
max deviation of velocity	SV_{dev}	± 0.01 m/s			

Table 3-1

* Remark: see 6.5.1

3.2 Vertical deviations of the information layer

VERTICAL DEVIATIONS			target values for:		
parameter	abbre-viation	Red Book specification	measuring range	measuring accuracy	remarks
Maximum deviation	VD_{peak}	± 0.5 mm	0 ~ ±0.6 mm	± 25 µm	f < 500 Hz
max RMS value	VD_{rms}	0.4 mm	0 ~ 0.48 mm	± 20 µm	
Maximum acceleration	VAC	10 m/s^2	0 ~ 12 m/s^2	± 0.5 m/s^2	
Maximum deviation	VN *	± 1 µm	0 ~ ±1.2 µm	± 0.1 µm	f > 500 Hz

Table 3-2

* Remark: The Vertical Noise and Acceleration meant in this context, is the noise in the vertical tracking signal caused by deviations of the reflective information layer from the reference plane in vertical direction.

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3.3 Radial deviations of the track

RADIAL DEVIATIONS			target values for:		
parameter	abbre-viation	Red Book specification	measuring range	measuring accuracy	remarks
Max Eccentricity (=Radial Deviations)	Ecc	± 70 µm	0 ~ ±105 µm ±105 ~ ±140µm	± 3.5 µm ± 5 µm	f < 500 Hz
Maximum acceleration	RAC	0.4 m/s^2	0 ~ 0.6 m/s^2 0.6 ~ 0.8 m/s^2	± 0.02 m/s^2 ± 0.03 m/s^2	
Residual error signal (radial noise)	RN	see track following			f > 500 Hz

Table 3-3

3.4 Track following signal

TRACK FOLLOWING SIGNAL			target values for:		
parameter	abbre-viation	Red Book specification	measuring range	measuring accuracy	remarks
Push-pull	PP	0.04 ~ 0.09	0.03 ~ 0.13	± 0.002	at 0.1 µm radial offset
max variation of PP	PP_{var}	± 15 %			
Radial contrast	RC	0.3 ~ 0.6	0.2 ~ 0.8	± 0.03	Orange Book specification
Radial noise	RN *	< 0.03 µm (RMS)	0 ~ 0.045 µm 0.045~0.06 µm	± 3 nm ± 4.5 nm	500 Hz < f .. .. f < 10 kHz
Single frequency noise (scanning filter bandwidth =100 Hz)		< 0,01 µm (RMS)			500 Hz < f .. .. f < 10 kHz
Local defects	**	no track jumps			

Table 3-4

* Remark: The Radial Noise and Acceleration meant in this context, is the noise in the radial tracking signal caused by deviations of the tracks from their nominal position in radial direction.

** Remark: Local defects, like air bubbles, black spots and scratches, can cause peaks in the Radial Noise and Acceleration and the Vertical Noise and Acceleration signals. These peaks should not be interpreted as Radial, respectively Vertical Noise or Acceleration. According to the Red Book local defects shall not generate track jumping (see Red Book 15.3). Local defects usually can be identified, because they also generate drop-outs in the HF-signal, peaks in the BLER count and burst errors.

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3.5 HF signal

HF SIGNAL				target values for:		
parameter	abbre-viation	Red Book specification		measuring range	measuring accuracy	remarks
Blank area reflectivity	R_0	> 0.7		0.2 ~ 1.0 for HF level measurements	± 0.02	Red Book attachm. 1(i)
Reflectivity of I_{top} (parallel reference)	$R_{top-par}$	> 0.65			± 0.02	Orange Book specification
Reflectivity of I_{top} (focused reference)	$R_{top-foc}$	> 0.58			± 0.02	Alternative specification: see 6.4.2
max variation of reflectivity	$I_{top-var}$	± 3 %				Red Book attachm. 2
I_3 / I_{top}		0.3 ~ 0.7			± 0.02	
I_{11} / I_{top}		≥ 0.6			± 0.02	
Asymmetry	ASYM	< 0.2		0 ~ ±0.28	± 0.02	recomm.: -0.15 ~ +0.05
Cross talk	CT	< 0.5		0 ~ 0.40 0.40 ~ 0.75	± 0.05 ± 0.025	
Jitter	JIT	< 35 ns (1 σ)		0 ~ 35 ns 35 ~ 50 ns	± 2 ns ± 5 ns	for each pit & land
Effect Length	EFL	PITS: 660 ± 40 910 ± 42.5 1165 ± 45 1400 ± 47.5 1635 ± 50 1875 ± 52.5 2110 ± 55 2340 ± 57.5 2570 ± 60	LANDS: 675 ± 40 925 ± 42.5 1165 ± 45 1400 ± 47.5 1635 ± 50 1870 ± 52.5 2105 ± 55 2335 ± 57.5 2560 ± 60	nominal value ± 115 ns (= nT ± ½T)	± 5 ns	Run-length: 3T 4T 5T 6T 7T 8T 9T 10T 11T
Time error due to frequency modulation of the channel bit rate		< 50 ns_{p-p}				f_{mod} > 4 kHz
		< 4000/f_{mod}*50 ns_{p-p}				f_{mod} < 4 kHz
Block Error Rate * (BLER_10)	BLER	< 220 counts/sec (averaged over any 10 seconds)		0 ~ 7350 counts/sec	±10% ±5 counts	accuracy ≡ repeatability
Burst Error Length **	BERL	< 5 C1 blocks		0 ~ 10		

Table 3-5

* Remark: Because the BLER is influenced by all player parts and could suffer from “error

propagation" due to for instance "sync loss" of the decoder, the accuracy requirement could be difficult to realize. Therefore the repeatability on one single CD-RMS shall fulfil the above requirement, while the reproducibility, when compared to an other CD-RMS, should be as good as possible.

** Remark: Local defects, like air bubbles, black spots, scratches and finger prints, can cause several successive frames to be erroneous. These errors are called "burst errors". The specification for the burst errors in the Red Book is based on an error correction system with a single error correcting C1 decoder and a single error correcting C2 decoder. No errors are allowed that are uncorrectable for such a decoder.
This means that the C2 decoder should not encounter more than 1 error in any C2 frame, or the C1 decoder should not detect a burst of 5 or more successive uncorrectable C1 frames (≥ 2 errors per frame). See Red Book attachment 4: the given value of 7 is formally not correct, however with today's decoders, capable of correcting double errors, the value of 7 will not cause problems.

3.6 Local defects

Local defects shall not exceed the following specifications:

air bubbles	$\varnothing < 100\ \mu m$
black spots	$\varnothing < 200\ \mu m$
black spots without birefringent area	$\varnothing < 300\ \mu m$
distance along the track between defects	> 20 mm

3.7 Decoded signals

The following table can be used by disc manufacturers to record their own individual quality requirements.

Recommended decoded signal measurements				
parameter	abbre-viation	individual specification	accuracy	remarks
all measured in 1 second periods		see 6.3 & 6.3.1		
all C1 errors	BLER_1			= E11 + E21 + E31
C1 single errors	E11			
C1 double errors	E21			
C1 ≥ triple errors	E31			
C1 burst error length	BERL			
C2 single errors	E12			
C2 double errors	E22			
C2 ≥ triple errors	E32			
C2 burst error length	C2_BERL			
C2 uncorrectable	UNCORR			

Table 3-6

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4 CD Reference Measuring System player components

4.1 Introduction

To be able to measure also discs being at, or even over the limits of the CD-standard, the player shall have such characteristics that it gives reasonable margins on all functions. However the bandwidth of the servo systems shall not be chosen very much higher than really needed. A servo system with a high bandwidth becomes more sensitive for disturbances and stability problems can be expected due to parasitic mechanical resonances in the system.
This means that if certain actual conditions are different from the standard specification, the error signals shall be compensated for those conditions before they are interpreted (see A.1.2).
A block diagram for a general CD player with its main functions is given in C.1. The basic accuracy of all parameters shall be better than 10%, unless specified otherwise.

4.2 Optical Pickup

The READ-OUT optical pick-up according to Red Book or IEC 908 has too wide margins (especially for the RIM intensity) to give good reproducibility on all measurements. Therefore the specifications of the READ-OUT optics for a CD-RMS are more tight. The wavelength range has been reduced to be able to measure CD-R discs as well.

wavelength:	$\lambda = 785^{+/-5}$ nm
RIN of the Laser:	< -130 dB/Hz
polarization:	circular
ellipticity:	$\Delta\phi = 90^{+/-10}$ deg
	(retardation of p and s components)
numerical aperture:	$0.45^{+/-0.01}$
intensity at the rim	
in radial direction:	50 ~ 80 %
in tangential direction:	> 70 %
wavefront distortion:	< 0.05 λ

The objective lens shall be compensated for spherical aberrations as caused by a parallel substrate with a thickness of 1.2 mm and a refractive index of 1.55.

4.3 Detection optics

The design of the (detection) optics in connection with the servo systems shall be such, that there is only a negligible influence of the focusing and radial tracking methods on the detected signals. Especially in the case of a two-stage radial tracking servo, where the objective lens moves in the laser beam, the optical power in the read-out spot might show variations, which could influence several signals, such as I_{top} and PP. These effects shall be avoided or reduced as much as possible.

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Detection method for parameter measurements:
HF signal: central aperture sum signal
track following signal: split diode difference signal
The photo-diodes shall be optimized for low noise contribution, in such a way that the laser diode is the dominating noise source.

Detection method for radial tracking and focusing:
The error signals for the actual radial tracking and focusing servo systems can be derived in several alternative ways.
For reliable deviation and noise measurements it is required that the focus error signal has a linear range of at least ± 3 μm and the radial error signal has a linear range of at least ± 0.13 μm (linear signal-to-distance relation within ± 5%).

4.4 Photo-diode pre-amplifiers

DC coupled: to measure I_{top} and other DC components and to preserve asymmetry.
For the HF signal: bandwidth > 3 MHZ (no phase distortion on the EFM); step-response shall be free of overshoots.
For track following signal: 1st order low-pass characteristic with τ = 15 μsec (10 kHz).
For focusing signal: 1st order low-pass characteristic with τ = 15 μsec (10 kHz).
The pre-amplifiers shall be optimized for low noise contribution, in such a way that the laser diode is the dominating noise source.

4.5 HF filtering

To reach sufficient suppression of high frequency noise (above the EFM bandwidth), a 5th order Bessel filter (constant group-delay) is added. Such a filter causes minimum phase distortion (time errors) in the HF signal.

5th order low-pass Bessel filter, -3 dB at f_{-3} = 1.5 MHZ:

$$H(f) = \frac{1}{\left(1 + 0.666j*\left(\frac{f}{f_{-3}}\right)\right)\left(1 + 0.622j*\left(\frac{f}{f_{-3}}\right) - 0.325*\left(\frac{f}{f_{-3}}\right)^2\right)\left(1 + 1.14j*\left(\frac{f}{f_{-3}}\right) - 0.413*\left(\frac{f}{f_{-3}}\right)^2\right)}$$

The bandwidth of 1.5 MHz has been chosen because this preserves the 2nd harmonics for all of the EFM frequencies (max ≡ I_3 ≡ 720 kHz), which contribute to the asymmetry. It also matches to the optical cut-off frequency:

$$f_{cut-off} = \left(\frac{2*NA}{\lambda}\right)*v = \left(\frac{2*0.45}{0.78*10^{-6}}\right)*1.3 = 1.5\ MHz$$

High-pass filtering (AC-coupling) with τ = 100 μsec (IEC 908).
If AC-coupling is applied between more stages, there shall be only one with the above specified time-constant; all others shall have a time-constant τ >> 100 μsec.

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4.6 HF MTF equalization

The MTF equalization shall not cause phase distortion or Inter-Symbol Interference (time errors) in the EFM signal. A 2nd order high frequency lift, phase-compensated with an all-pass network, fulfils this requirement and gives the needed MTF equalization (see C.2 A: $\tau = R*C = 1 / (2\pi*f_{+6})$.

2nd order high frequency lift, phase compensated, +6 dB at f_{+6} = 950 kHz:

$$H(f) = \left(1 + (\frac{f}{f_{+6}})^2\right)$$

As an alternative (digital) equalizer, a transversal filter with 3 taps can be applied (see C.2 B). The delays are 1 T (T = 1 / $f_{EFM\text{-}clock}$ = 231 nsec) and the transfer function is:

$$H(z) = 1*z^{-1} - 0.25*(1 + z^{-2})$$

Because this transfer function does not have the continuing frequency lift as in the analogue equalizer, the low-pass Bessel filter can be of a lower order (e.g. 3) and the -3 dB frequency can be higher (e.g. 2.5 MHZ).

4.7 EFM slicer

An adaptive slicer shall be used, with an asymmetry correction by means of a feedback of the DC content of the digitalized EFM signal.
Since the EFM signal has been made DC-free during modulation by means of a DSV control with the merging bits, the output of the slicer should have an average duty cycle of 50%. If this is not the case, the DC levels on the input of the comparator will change in such a way, that the output signal becomes more symmetric. A double, balanced feedback increases the loopgain and prevents the need for an adjustable comparator input voltage level (see C.3).
For a recommended input signal level of 0.5 ~ 1 Volt peak-to-peak, the closed loop -3 dB bandwidth of the feedback slicer shall be about 1 kHz. For the implementation of C.3 this results in a time-constant $\tau = R*C \approx 1$ msec.

4.8 EFM bitclock regeneration

The PLL for the EFM bitclock regeneration can be characterized in the same way as the servo loops. However, it is more common to specify the 2nd order frequency characteristic of a PLL by its natural frequency f_N and its damping factor z (see C.4).
With a low f_N the PLL is less sensitive for disturbances, and a high z gives good capturing properties.

$$1.5 \text{ kHz} < f_N < 2.5 \text{ kHz} \;\; ; \;\; 2 < z < 4$$

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4.9 Focus servo

Because the spot quality is heavily depending on the focusing, the focus servo is a critical parameter in the player's ability to read-out signals from the disc. Therefore sufficient margin has to be taken into account. With a margin of about 5 times the minimum requirements for the vertical tracking error, we can derive a system, which is able to follow most of the discs and is still robust enough against disturbances.
The residual DC focusing error, due to for instance system offsets, shall be < 0.1 μm (calibrated with a disc of thickness 1.2 mm and a refractive index of 1.55; see also 6.2.4). Special tricks in the servo system, like e.g. switching to open loop on disturbances, are not allowed if they influence the measuring results.

The actual focus servo shall be a second order system according to the general servo model given in Annex A with the following parameters:

$$f_0 = 1500 \text{ Hz} ; \ c = 3$$

4.10 Radial servo

Although less critical than the focus servo, also for the radial servo sufficient margin is taken into account. With a margin of about 4 times the minimum requirements for the radial tracking error, a system will result, which is able to follow most of the discs and is still robust enough against disturbances.
The residual DC tracking error, due to for instance system offsets, shall be < 0.05 μm. Special tricks in the servo system, like e.g. switching to open loop on disturbances or wobble procedures for offset compensation, are not allowed if they influence the measuring results.

The actual radial servo shall be a second order system according to the general servo model given in Annex A with the following parameters:

$$f_0 = 600 \text{ Hz} ; \ c = 3$$

4.11 Rotation servo

The influence of the rotation servo system on measurement results is only minor. Only radial track deviations (like eccentricity), may result in tangential track velocity variations, which could cause some extra jitter and effect length deviation. Usually these can be neglected; if needed they could be compensated in software by correcting the results for the velocity variations.

The following parameters are given for a control system according to the general servo model as described in Annex A:

$$f_0 = \text{about } 10 \text{ Hz at radius } 25 \text{ mm} ; \ c = \text{about } 3$$

For the measurement of single frequency time errors in the EFM signal (see Red Book, attachment 15: "Frequency modulation of the channel bit frequency") it is recommended to use a lower bandwidth (e.g. ≤ 1 Hz).

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4.12 Mechanical design

The mechanical design of the system will not be specified in detail. However because of the very stringent specifications on measurement accuracy and reproducibility at least the following mechanical parameters have to be limited, due to their influence on the specified measurements:

- Eccentricity of the CD clamping.
- Fluctuation of the distance between the reference plane determined by the clamping unit and the lens of the optical pick-up unit over the total, recorded disc surface ("wobbling turn-table").
- Clamping force well within Red Book limits (influence due to bending of skewed discs).
- Any mechanical resonances.

special attention:
Special attention should be paid to avoid possible mechanical or optical sources of cross-talk between the rotation, focus and radial servo.

5 Measuring methods and conditions

Since this specification deals with a reference measuring system, the measuring conditions and methods to be used in the system have to be specified in order to get comparable results amongst players from different manufacturers. In this chapter an overview is given of several general measuring methods. The implementation of these methods is not limited to hardware. If possible, software solutions can also be utilized.

5.1 General

The system should be able to work within its ranges and accuracies in climatological conditions according to IEC 908:

ambient temperature	15 to 35 ºC,
relative humidity	45 to 75 %,
air pressure	86 to 106 kPa.

In order to ensure proper and repeatable servo related disc parameter measurements, the system mechanics have to be placed such, that it is vibration isolated and protected against acoustic influences during measurements.

All measurements have to be related to the absolute time on the disc (ATIME), except for the Lead-in area.
The measurements have to include the following disc areas:

- Lead-in area
- Program area
- Lead-out area until the end of the disc.

5.2 Signal Pre-processing

Before signals can be measured, in general they need some pre-processing like filtering, rectifying, averaging, etc.

5.2.1 Basic Filter types

All filters used for measuring purposes are 2nd order Butterworth types, unless specified otherwise. All specified filter frequencies are related to the nominal (1x) scanning velocity and their accuracy shall be better than ± 5%. For high-speed (Nx) measuring players, the frequency values have to be adapted accordingly.

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5.2.2 Peak detection

Peak detection of signals shall be done with a "diode detector" (or a process that delivers comparable results). The drop-out voltage of the diode shall be made negligible. $\tau = R*C$ is the time-constant of the peak detector.
A peak detector works on the total composite signal and can not be made selective for certain components out of the signal.

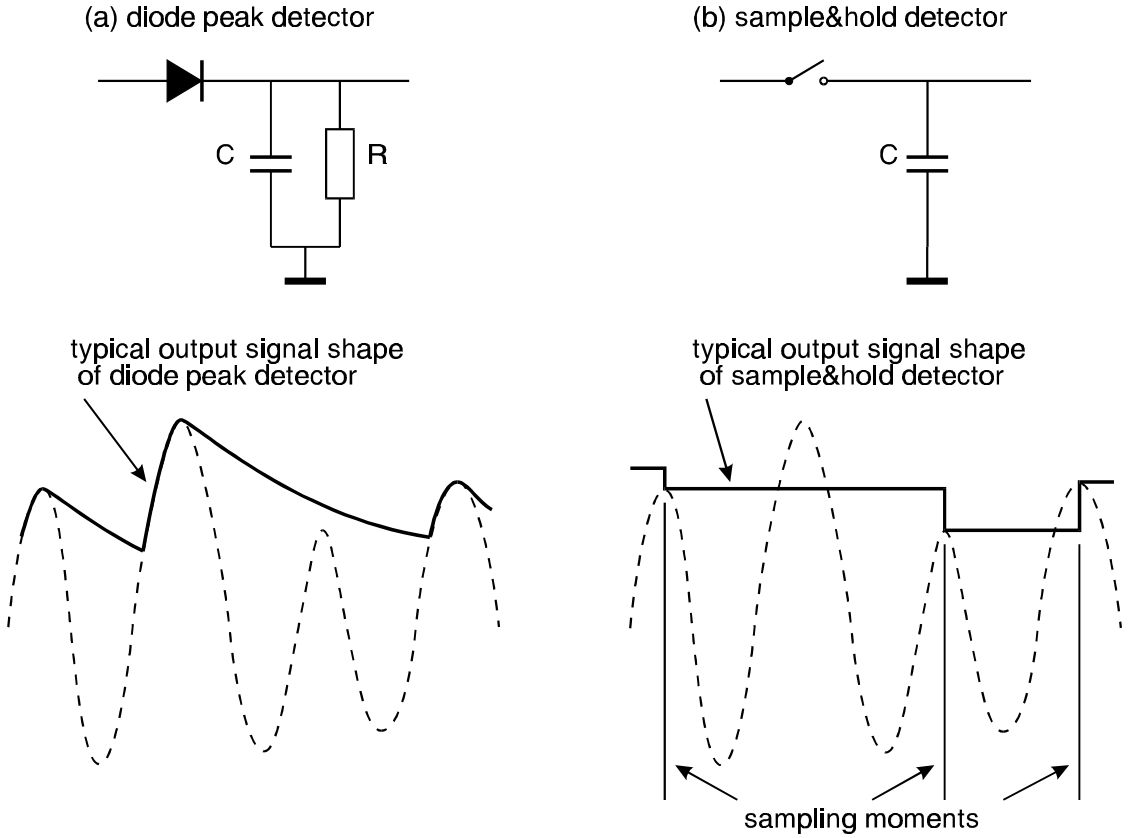

Figure 2 Examples of peak detection (a) and sample&hold detection (b)

5.2.3 Sample&hold detection

The envelope of a signal, or of certain components out of a signal, is determined by a sample&hold process. After each sample taken, the value is held until the next sample.
The samples need not to be equidistant. A sampler can selectively take samples from distinguishable components out of a signal.

5.2.4 RMS processing

For several parameters the RMS value has to be determined. After squaring the input signal, the squared signal shall be averaged by a first order integrator with transfer function: $H(p) = 1 / (1 + p.\tau)$ with τ being the integration time-constant.
The output signal of the RMS processor is the square-root from the averaged (DC) square signal.

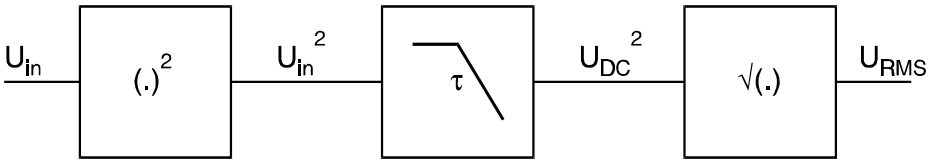

Figure 3 Typical RMS processor

The input part of the RMS processor shall be able to handle input signals with a specified maximum peak level (CREST factor = ratio between peak value and RMS value).

5.2.5 Stray Elimination

Sometimes a series of measurements can show a few results, which are very different from the vast majority of the values. For some measurements it might be better not to take these values into account, for instance in the averaging process or in the calculation of the variation.
Stray elimination could be performed in software, after all measurement values are taken (post-processing), or the related signal could be pre-processed, e.g. by filtering, in such away that "strange" values are smoothed out.
The stray elimination will be defined for every measurement separately if it is needed.

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5.3 Basic Measuring Methods

In the CD-RMS 5 types of parameters can be found:

- **AAP**	: Analogue Averaged Parameters	(e.g.: I_{11}/I_{top}, Asymmetry, etc)
- **APP**	: Analogue Peak Parameters	(e.g.: RN, accelerations, etc)
- **CP**	: Count Parameters	(e.g.: BLER, etc)
- **DF**	: Data Format	(e.g.: subcode, CD-ROM, etc)
- **GP**	: Geometrical Parameters	(e.g.: program start radius, scanning velocity, track pitch, etc)

In the following sections detailed information about the related measuring methods is given.

5.3.1 APP and CP - Basic Measuring Method

All **A**nalogue **P**eak **P**arameters and **C**ount **P**arameters within the program area should be evaluated continuously and read out per second (1 value per second).
The one second measuring windows are synchronized to the ATIME from the disc and start at the beginning of each subcode frame with ATIME "min:sec:00" and end immediately after the next subcode frame with ATIME "min:sec:74", followed by a reset in order to prevent influences from the previous second.

5.3.2 AAP - Basic Measuring Method

Due to for instance skew, birefringence or thickness variations over one revolution, some parameters can have angular variations.
In order to get high repeatability and reproducibility for the **A**nalogue **A**veraged **P**arameters, the averaging process has to be done on measurement results out of a number of complete revolutions. To get reliably averaged data, a different method for choosing the measuring window is used. The following procedure should be applied in order to get one average value per ATIME second:

> After occurrence of a subcode frame with ATIME "min:sec:74", the command *"start sampling"* is given by the measuring system at the next revolutional trigger pulse (one pulse per revolution). Sampling is stopped (or the next measurement is started) at the first revolutional trigger pulse after the next subcode frame with ATIME "min:sec:74".

The resulting measuring period is variable and dependent on the revolutional speed of the disc, which can vary from 8.9 Hz at R=25 mm & v=1.4 m/sec to 3.3 Hz at R=58 mm & v=1.2 m/sec. The time for 1 revolution is: 0.112 sec < 1 rev < 0.304 sec.

$$\textit{Measuring period} = 1\ \textit{sec} \pm 1\ \textit{revolution}$$

For each ATIME second the AVG value of the parameter is calculated by adding all samples and dividing this sum by the number of samples taken during the related measuring period. Furthermore the MIN and MAX values of the parameter, found during the related measuring period, are stored for calculating the signal variation after all measurements are done (see 5.3.4).
The number of samples taken during one revolution has to be based on the maximum signal frequency and the signal modulation. To be sure that all MAX and MIN values are detected

with sufficient accuracy, the sampling frequency shall be > 20x the upper filter frequency. The samples have to be equally distributed in time (fixed sampling frequency, independent of the revolutional speed).

5.3.3 AAP@ORL (AAP at Open Radial Loop) - Basic Measuring Method

Some parameters (Push-pull, Cross Talk, Radial Contrast) have to be measured by crossing tracks, which can be accomplished in an open radial servo loop condition.
In order to get high repeatability and reproducibility of average values in case of angular variations during a revolution and to be independent on eccentricity, for these measurements the following measuring method is recommended:

> After positioning the optical pick-up at the specified ATIME, the rotation speed is set at a fixed number of revolutions per second (about 2.5 Hz) and the radial servo loop is switched off, by which the pick-up is kept fixed at the actual position.
> To ensure sufficient track crossings, independent of the eccentricity of the disc and of the player, an active radial wobble-movement of the pick-up system is now applied. This movement shall be about sinusoidal with a frequency 30~50 Hz and a peak-peak displacement of 15~25 tracks.

Due to the low rotation speed of the disc and the relatively high wobble frequency, in this way a "quasi-stationary" track-crossing procedure is realized with a reasonably fixed number of tracks being crossed during each wobble cycle.
Samples taken during "incomplete track crossings" shall be neglected (during the peaks of the wobble signal, when the pick-up unit is changing its moving direction, the last track is often "touched" instead of "crossed"; see Figure 5).

The averaging of the signal shall be performed over the samples from a number of complete revolutions (1 or more). For each selected ATIME (because several tracks are involved in each measurement, it is useless to measure every ATIME second) the AVG value of the parameter is calculated by adding all samples and dividing this sum by the number of samples, taken during the related measuring period. Furthermore the MIN and MAX values of the parameter, found during the related measuring period, are stored for calculating the signal variation after all measurements are done (see 5.3.4).
The number of samples taken during one revolution has to be based on the maximum signal frequency and the signal modulation. To be sure that all MAX and MIN values are detected with sufficient accuracy, the sampling frequency shall be > 20x the upper filter frequency. The samples have to be equally distributed in time (fixed sampling frequency).

Example:
Suppose the parameter X is sinusoidal depending on the radial position of the spot relative to the tracks. X can be expressed in the following way (see for example Push-pull in Figure 10):

$$X = X_{peak} * \sin\left(2.\pi.\frac{\Delta R\ [\mu m]}{p\ [\mu m]}\right), \quad \text{in which p = trackpitch}$$

The radial position of the spot relative to the tracks can be expressed by the following function of time (expressed in number of tracks):

$$\Delta R(t) = W * \sin(2.\pi.f_w.t) + E * \sin(2.\pi.f_r.t) \quad [\text{tracks}]$$

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The first part represents the wobble movement of the pick-up, while the second part represents the track movement due to the eccentricity of the disc + player, in which:

W = wobble amplitude = 10 tracks,
f_w = wobble frequency = 40 Hz,
E = eccentricity = max 50 tracks,
f_r = rotation frequency = 2.5 Hz.

The number of tracks passing the spot per second can be calculated by differentiating the above equation:

$$v(t) = \frac{d}{dt}\{\Delta R(t)\} = 2.\pi.f_w.W*\cos(2.\pi.f_w.t) + 2.\pi.f_r.E*\cos(2.\pi.f_r.t)$$

When f_w and f_r are uncorrelated, the maximum speed with which tracks are passing the spot is:

$$v_{max} = 2.p.f_w.W \pm 2.p.f_r.E \approx 2500 \pm 800 = 1700 \sim 3300 \ [tracks/second]$$

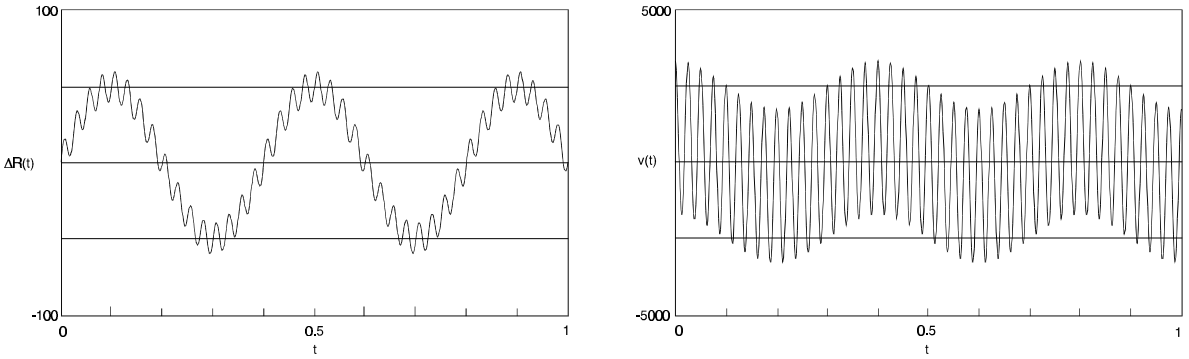

Figure 4 Position and speed of spot relative to tracks due to wobble + eccentricity

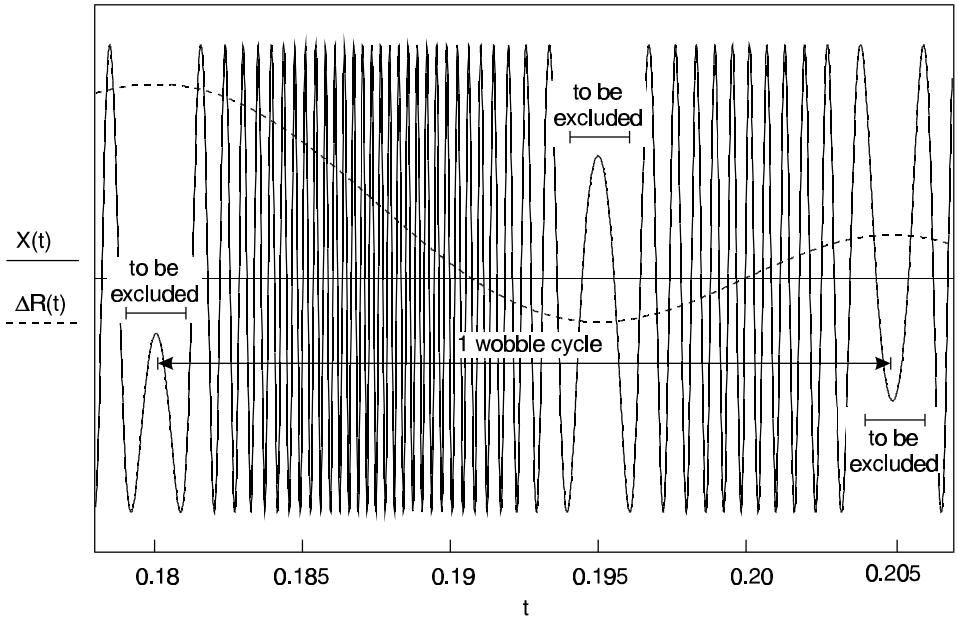

Figure 5 Parameter X(t) due to wobble + eccentricity

5.3.4 Signal variation (Relative Range)

For some parameters like Reflection and Push-pull, maximum variations are specified in the Red Book.
Definition of the variation of parameter x is:

$$\text{variation} = \frac{x - AVG(x)}{AVG(x)} * 100\%$$

MAX(x) and MIN(x) are the maximum and minimum of all the values of x, measured during the whole checking-time (CD playing-time), unless otherwise specified.
From these MAX and MIN values, the highest positive and negative variation is defined:

$$VAR_{pos}(x) = \frac{MAX(x) - AVG(x)}{AVG(x)} * 100\%$$

$$VAR_{neg}(x) = \frac{MIN(x) - AVG(x)}{AVG(x)} * 100\%$$

The relative range is defined as the range of values between VAR_{neg} and VAR_{pos} :

$$REL_RNG(x) = \text{range}\,[\,VAR_{neg}(x) \sim VAR_{pos}(x)]$$

5.3.5 Signal Normalization

The pick-up detector signals are influenced by skew, birefringence, thickness, reflection and laser power fluctuations. In order to obtain high reproducibility, the pick-up detector signals shall be normalized. Normalization in this context means:

dividing the average value of the parameter by the average value of I_{top} from the same radial position on the disc (ATIME). For the definition of I_{top} see 6.1.

$$AVG_{norm}(x) = \frac{AVG(x)}{AVG(I_{top})}$$

5.3.6 Signal Calibrations

To cancel possible differences in the measuring results of different players and to increase the basic accuracy, a player shall be calibrated with reference discs.
These discs contain tracks with pre-defined values for parameters, such as e.g. I_3/I_{top}, I_{11}/I_{top} and Push-pull. From the measurement results of these reference discs, correction factors can be derived to cancel the differences given by the player.

5.3.7 Track jumps

Track-jumps, etc., can be detected by the system because of ATIME discontinuities. The ATIME where such an error occurs, shall be recorded.

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6 Definitions of measuring-signals

6.1 Read-out related signals

In the following 2 figures the definitions of the HF signal levels and measuring windows are illustrated.

To exclude the influence of over-shoots and/or under-shoots in the HF-signals, the sampling for the determination of the I_n "high" and I_n "low" levels shall be done in the middle of a run-length in a window of about 1T~2T.

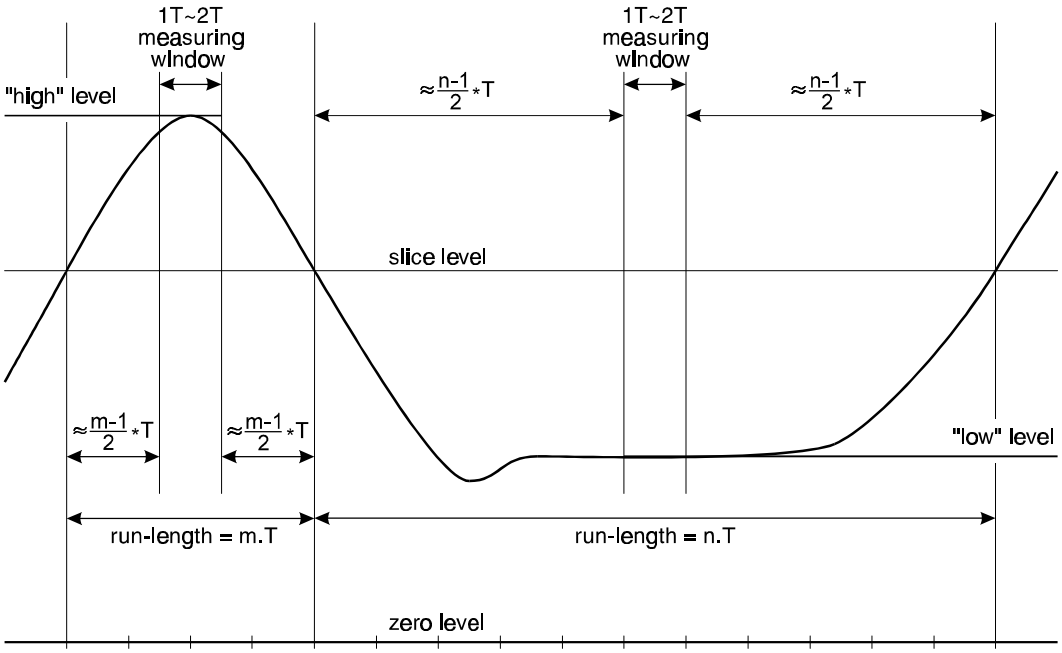

Figure 6 Definition of the measuring windows for sampling the I_n levels

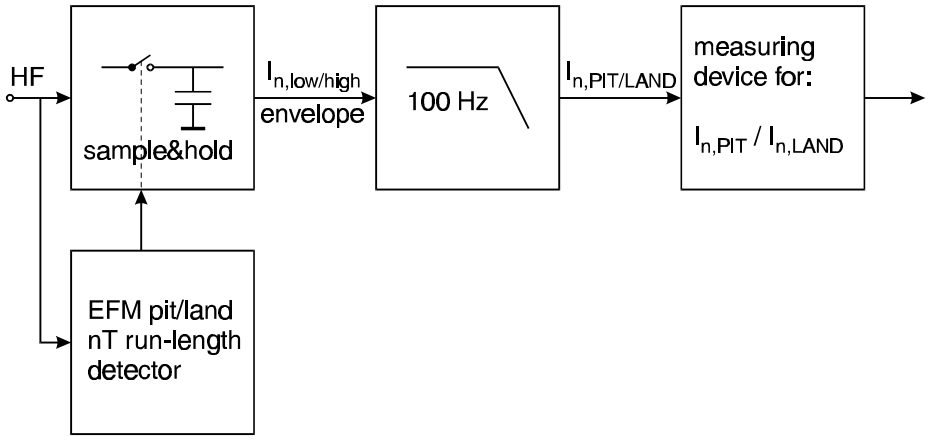

Figure 7 Measuring set-up for $I_{n,pit}$ or $I_{n,land}$ signals

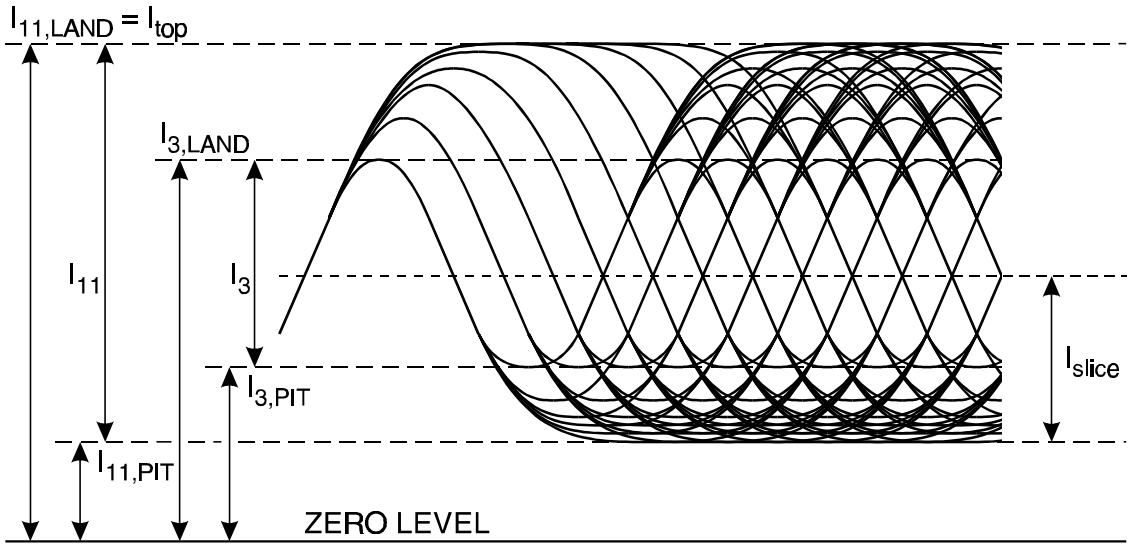

Figure 8 Definition of the HF levels

The meaning of "envelope" is explained in 5.2.3.

$I_{11,LAND}$ is: the envelope of the I_{11} "high" signal levels out of the HF signal. The envelope is filtered by a 100 Hz low-pass filter.

$I_{11,PIT}$ is: the envelope of the I_{11} "low" signal levels out of the HF signal. The envelope is filtered by a 100 Hz low-pass filter.

$I_{11} = I_{11,LAND} - I_{11,PIT}$ (≡ peak-peak value of the HF signal with the lowest frequency)

$I_{top} = I_{11,LAND}$

$I_{3,LAND}$ is: the envelope of the I_3 "high" signal levels out of the HF signal. The envelope is filtered by a 100 Hz low-pass filter.

$I_{3,PIT}$ is: the envelope of the I_3 "low" signal levels out of the HF signal. The envelope is filtered by a 100 Hz low-pass filter.

$I_3 = I_{3,LAND} - I_{3,PIT}$ (≡ peak-peak value of the HF signal with the highest frequency)

I_{SLICE} is: the detection level at the input of the EFM slicer, which will result in a digitalized output with an average duty cycle of 50 %.

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6.1.1 Reflection: RFL (AAP method)

Measurement of the real reflection of a disc in a player is not possible and because of the complexity of the system, the "Ulbricht sphere" as mentioned in the Red Book will not be described in this document. An indication for the value of the reflection can be determined by comparing the I_{top} value of the disc under investigation with the I_{top} value of a reference disc with a known reflection value (see Red Book 8.4 and its attachment 1, and Orange Book attachment B2).
However, I_{top} is not only depending on the reflectivity of the disc, but is also influenced by effects like birefringence and disc skew. It is a combination of all these parameters that is measured. If the value of RFL is outside the specification limits, this does not mean immediately that the reflectivity of the disc is too low. A more detailed analysis on specialized equipment is needed then, to determine the origins of the low value.

$I_{top,DUI}$ is the I_{top} value measured on the disc under investigation.
$I_{top,RD}$ is the I_{top} value measured on the reference disc.
RFL_{RD} is the specified RFL value of the reference disc.

$$RFL = \frac{AVG(I_{top,DUI})}{AVG(I_{top,RD})} * RFL_{RD}$$

The MIN and MAX values per revolution of $I_{top,DUI}$ are needed to calculate the signal variation.
RFL_{RD} can be specified in some alternative ways that are described in 6.4.2

6.1.2 I_{top} Variation: $I_{top,VAR}$ (AAP method)

$I_{top,VAR}$ is defined as the relative range of the I_{top} signal. (see 5.3.4 and 6.1.1)

$$I_{top,VAR} = \text{range}\left[\left(\frac{I_{top,MIN} - AVG(I_{top})}{AVG(I_{top})} * 100\%\right) \sim \left(\frac{I_{top,MAX} - AVG(I_{top})}{AVG(I_{top})} * 100\%\right)\right]$$

This relates to the parameter "Reflection variation" as given in the Red Book (8.5 and attachment 2). However, as with I_{top}, also $I_{top,VAR}$ will be depending on other effects like birefringence and disc skew.
$I_{top,VAR}$ is to be measured per revolution.

6.1.3 I_{11}/I_{top} (AAP method)

I_{11}/I_{top} is the difference between $I_{11,LAND}$ and $I_{11,PIT}$, normalized by I_{top}.

$$I_{11}/I_{top} = \frac{AVG(I_{11,LAND} - I_{11,PIT})}{AVG(I_{top})} = 1 - AVG_{norm}(I_{11,PIT})$$

6.1.4 I_3/I_{top} (AAP method)

I_3/I_{top} is the difference between $I_{3,LAND}$ and $I_{3,PIT}$, normalized by I_{top}.

$$I_3/I_{top} = \frac{AVG(I_{3,LAND} - I_{3,PIT})}{AVG(I_{top})} = AVG_{norm}(I_{3,LAND}) - AVG_{norm}(I_{3,PIT})$$

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6.1.5 Asymmetry: ASYM (AAP Method)

Asymmetry is defined in the Red Book and IEC 908 as:

$$\text{ASYM} = \left(\frac{\text{AVG}(I_{slice})}{\text{AVG}(I_{11})} - \frac{1}{2} \right) * 100\%$$

Because I_{slice} is not so easy to determine, another definition will be used, which results in about the same values.

ASYM will be defined as the relation between the I_{11} center-level and the I_3 center-level:

$$\text{ASYM} = \left(\frac{\frac{1}{2} * \text{AVG}(I_{3,LAND} + I_{3,PIT}) - \frac{1}{2} * \text{AVG}(I_{11,LAND} + I_{11,PIT})}{\text{AVG}(I_{11})} \right) * 100\%$$

$$= \left(- \frac{1 + \text{AVG}_{norm}(I_{11,PIT}) - \text{AVG}_{norm}(I_{3,LAND}) - \text{AVG}_{norm}(I_{3,PIT})}{2 * \{1 - \text{AVG}_{norm}(I_{11,PIT})\}} \right) * 100\%$$

6.1.6 Beta: β (AAP method)

(see Orange Book Part II chapter B3.3)

Beta is the difference between the positive and the negative peak levels of the AC-coupled HF signal, normalized by the peak-peak value. β is an alternative asymmetry parameter, which is very easy to measure.

After AC-coupling (time-constant about 100 μsec), the HF signal is sufficiently amplified, and the positive and negative parts of the signal are peak-detected with a time-constant of about 5 msec (see 5.2.2).

A_1 is the positive peak-detected signal out of the AC-coupled HF signal (corresponding to $I_{n,LAND}$).

A_2 is the negative peak-detected signal out of the AC-coupled HF signal (corresponding to $I_{n,PIT}$).

$$\beta = \text{AVG}\left(\frac{|A_1| - |A_2|}{|A_1| + |A_2|} \right)$$

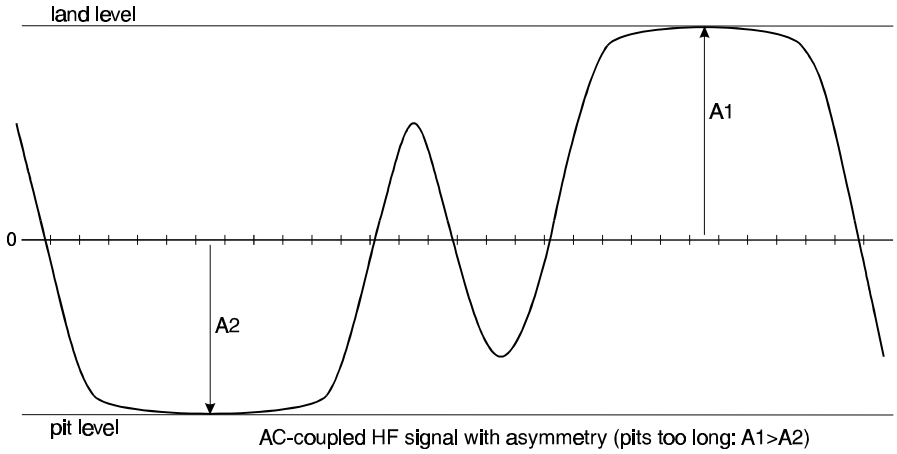

Figure 9 Definition of signal levels for β

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Or similar: β is the relation between the I_{11} center-level and the DC-level of the total HF signal.

HF_{DC} is the DC-level obtained after 100 Hz low-pass filtering the DC-coupled HF signal.

$$\beta = \left(\frac{\frac{1}{2} * AVG(I_{11,LAND} + I_{11,PIT}) - AVG(HF_{DC})}{\frac{1}{2} * AVG(I_{11})} \right)$$

$$= \left(\frac{1 + AVG_{norm}(I_{11,PIT}) - 2 * AVG_{norm}(HF_{DC})}{1 - AVG_{norm}(I_{11,PIT})} \right)$$

6.1.7 Jitter and Effect Length

The measuring method of jitter and effect length is given in an extension of the Red- and Yellow book. Because the jitter specification is meant to ensure the compatibility of discs and players, and players not always are equipped with MTF correction circuits, it is important to measure the jitter on the HF signal without MTF correction.
To measure the real pit/land jitter on the disc, other effects that could influence the jitter values should be excluded. Therefore jitter should be measured after:
- high-pass filtering: to remove low frequency disturbances caused by disc defects like dust, scratches and fingerprints,
- low-pass filtering: to remove high frequency noise.

To exclude the influence of the bitclock PLL, the jitter is measured relative to an absolute time reference.
The reference (X-tal) clock of the player shall have an accuracy better than $\pm$ 50 ppm.

The effect length errors can be divided into 2 classes:
- one is a fixed length deviation.
  The absolute value of these deviations is the same for all run-lengths and the sign (+/-) is opposite for pits and for lands. The result of this deviation is pure asymmetry and could be caused for instance by over/under exposure during recording.
- the other is a run-length dependent deviation.
  These deviations are different for different run-lengths and different for pits and lands. Especially the shorter pits are suffering from this phenomenon, which could be caused for instance by ISI and MTF limitations during recording.

The first class of the effect length errors is covered by the asymmetry specification.
The second class of the effect length errors is covered by the effect length and jitter specification and shall be measured after an asymmetry correction by means of an adaptive slicer has been applied to the signal.

At least an output must be available for the connection of an external Time Interval Analyzer (TIA).
It is also possible to implement the TIA function (with a time resolution of 5 nsec or better) into the CD-RMS. In case of a built-in TIA the Jitter and Effect Length values should be calculated per 10 seconds, triggered in the same way (ATIME related) as described for the APP and CP method.

6.1.8 Push-pull: PP (AAP@ORL method)

PP is the slope of the difference signal (I_1 - I_2), generated by the optical power difference in the reflected beam on 2 halves of a split diode at far field. The PP-signal shall be filtered by a 10 kHz, 5th order, Butterworth type, low-pass filter and normalized by I_{top} from the same radial position on the disc. This sharp filter is needed to reduce the noise caused by the low-frequency part of the EFM spectrum (especially at low revolution speeds).

For the measurement, the PP-signal is generated by crossing several tracks in an open loop condition of the radial servo system (see 5.3.3).

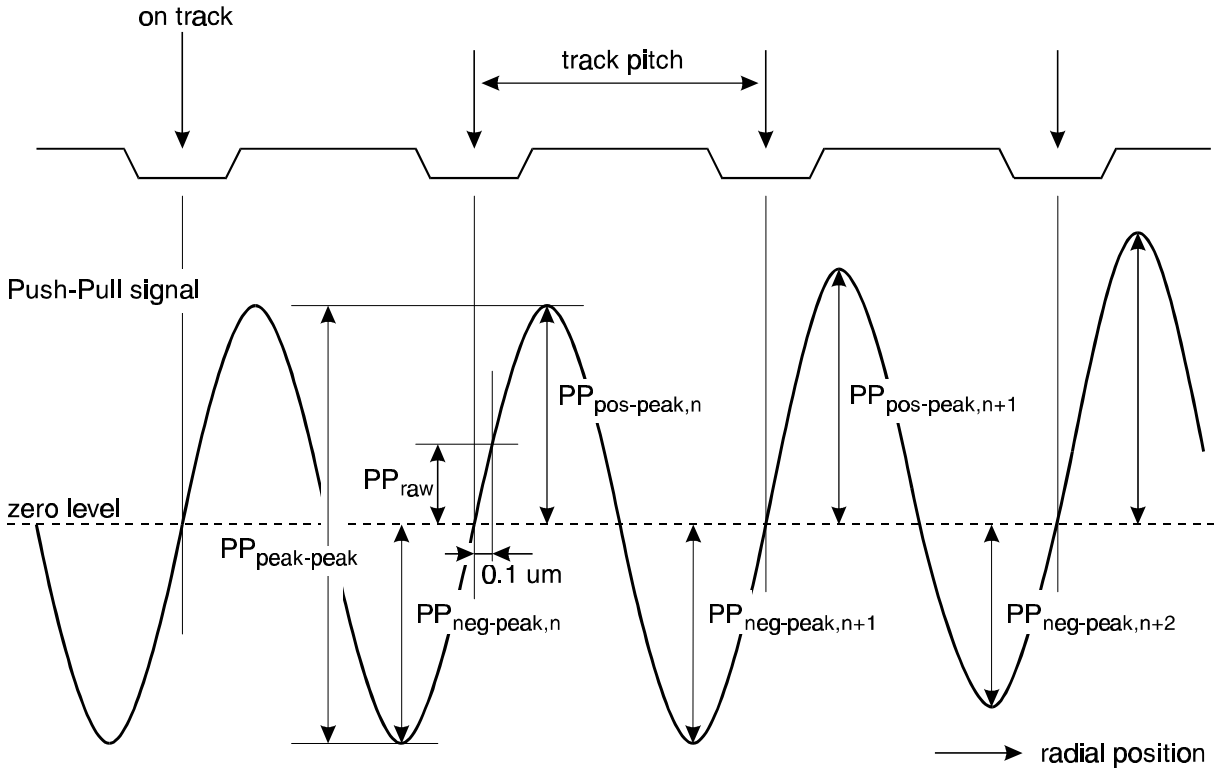

Figure 10 The radial tracking Push-pull signal

For the calculation of the PP value, the peak-to-peak signal amplitude is taken to eliminate offsets. $PP_{peak\text{-}peak}$ is determined by the difference of the sample&hold values of successive pairs of $PP_{neg\text{-}peak,n}$ and $PP_{pos\text{-}peak,n}$, which signal is filtered by a low-pass filter with a cut-off frequency equal to 10x the rotation frequency of the disc.
As an alternative for the sample&hold, a peak-to-peak detector with a time-constant equal to the period of the wobble frequency can be used (see 5.3.3).
Now the value corresponding to a radial track offset of 0.1 µm is calculated.

$$PP_{raw} = \frac{\frac{1}{2} * PP_{peak-peak}}{I_{top}} * \sin\left(2.\pi.\frac{0.1\,[\mu m]}{\text{trackpitch}\,[\mu m]}\right)$$

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Since the local track pitch is not known, the track pitch as given in the formula should be kept as a constant on the nominal value of 1.6 μm.
Therefore the Push-pull is defined as follows:

$$PP = \frac{AVG(PP_{peak-peak})}{AVG(I_{top})} * CONST; \quad CONST = \tfrac{1}{2} * \sin\left(2.\pi.\frac{0.1}{1.6}\right) = 0.1913$$

The averaging has to be done as described for "AAP at open radial loop" (wobble method). MIN and MAX values of the $PP_{peak\text{-}peak}$ values from all measuring positions on the CD are used to calculate the signal variation. Samples taken around the peaks of the wobble signal (a time interval of about 10% of the wobble period), should be ignored (see Figure 5).

If the wobble procedure as described in 5.3.3 is not used, the actual procedure shall deliver the same results (scaling of time-constants and filter bandwidths is important).

6.1.9 Push-pull Variation: PP_{VAR} (AAP@ORL method)

PP_{VAR} is defined as the relative range of the PP signal. (see 5.3.4 and 6.1.8)

$$PP_{VAR} = range\left[\left(\frac{PP_{peak-peak,MIN} - AVG(PP)}{AVG(PP)} * 100\%\right) \sim \left(\frac{PP_{peak-peak,MAX} - AVG(PP)}{AVG(PP)} * 100\%\right)\right]$$

As with I_{top} (see 6.1.1), also the PP signal may be depending on effects like disc skew and birefringence.

6.1.10 Cross Talk: CT (AAP method or AAP@ORL method)

CrossTalk (CT) is the ratio of the HF signal amplitude B between the tracks (occurring during track-crossings) and the HF signal amplitude A on the tracks.

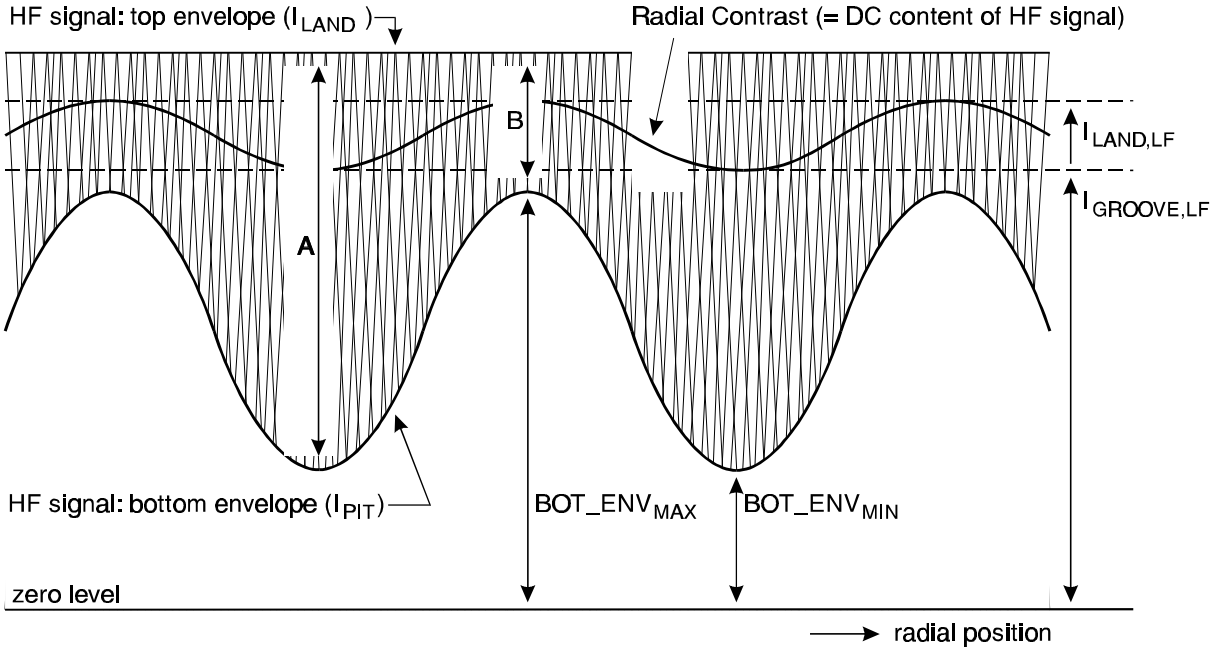

Figure 11 The Cross Talk and Radial Contrast signals during track crossings

The easiest way to measure the cross talk, is using a player with a radial servo system that can follow "between the tracks". This can usually be accomplished by inverting the polarity of the radial error signal.
In such a player the HF signal amplitude is measured twice with a peak-to-peak detector with time-constant = 5 msec (see 5.2.2):

- once with the normal radial error signal polarity, following the tracks (measuring amplitude A),
- and once with the radial error signal inverted, following between the tracks (measuring amplitude B).

$$CT\,[\%] = \frac{AVG(B)}{AVG(A)} * 100\% \quad \text{(AVG over number of complete revolutions)}$$

As an alternative the track-crossing method described in the "AAP at open (radial) loop" procedure can be used.
For the calculation successive pairs of BOT_ENV_{MIN} and BOT_ENV_{MAX} values (see also PP definitions) have to be taken. The averaging has to be done as described for "AAP at open (radial) loop" (wobble method).

$$CT\,[\%] = \frac{AVG(B)}{AVG(A)} * 100\% = \left(\frac{1 - AVG_{norm}(BOT_ENV_{MAX}}{1 - AVG_{norm}(BOT_ENV_{MIN}} \right) * 100\%$$

6.1.11 Radial Contrast: RC (AAP method or AAP@ORL method)

(see also Orange Book Part II: 1.4.3)

Radial Contrast (RC) is the difference of the DC-levels of the Cross Talk signal between the tracks (land) and on the tracks (groove) (see Figure 11). The HF signal is removed by a 10 kHz, 5th order Butterworth type, low-pass filter. The AC amplitude of the RC signal is normalized with the average DC-level.
The same measuring procedures can be followed as described in 6.1.10 for measuring the Cross Talk.

$I_{LAND,LF}$ (land intensity) is the DC-signal level out of the 10 kHz low-pass filtered HF signal, when following between the tracks.
$I_{GROOVE,LF}$ (groove intensity) is the DC-signal level out of the 10 kHz low-pass filtered HF signal, when following the tracks.

$$RC = \frac{AVG(I_{LAND,LF}) - AVG(I_{GROOVE,LF})}{\frac{1}{2} * \{AVG(I_{LAND,LF}) + AVG(I_{GROOVE,LF})\}}$$

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6.2 Servo related signals

In the CD-standard the radial and vertical parameters of the disc are defining the maximum deviations of the position of the actual track relative to an ideal track in a reference plane. This ideal track / reference plane are defined by the clamping area and the center hole.
The measured values within the specified frequency ranges should **not** show any influence from the vertical, radial and tangential servo methods used.
To be in conformance with the definitions, it might be necessary to compensate for the influences of the actual servo system. In case of a two step servo system (e.g. pick-up sledge and moving lens for the radial tracking servo system) a combination of the two driving signals might be needed, depending on the bandwidth of the two units.

6.2.1 Eccentricity: Ecc (APP method)

Eccentricity (Ecc) is about equivalent with the maximum radial deviation of a track from it's average position relative to the center hole of the disc, measured per revolution in the frequency range up to 500 Hz.

RAD_POS is the AC-coupled (< 1 Hz) and 500 Hz low-pass filtered radial tracking servo drive signal, compensated for the servo system and converted in such away that it represents the displacement of the track (see A.1.1 and C.6). A scaling function is applied to get a result in μm.

$$Ecc = scaling_function\{MAX|(RAD_POS)|\}$$

An easy alternative method for measuring the Ecc is achieved by switching off the radial tracking servo system and counting the number of tracks passing the optical pick-up. When the trackpitch is known, the Ecc can be calculated as:

Ecc = ¼ * (number of positive (or negative) zero crossings of
the radial tracking error signal during 1 revolution) * trackpitch

Remark 1: Strictly the used terminology is not correct: the first definition specifies the total "radial deviations", while eccentricity is just the offset of the center hole from the center of a circular track, which results in deviations with $f = f_{rotation}$. Unroundness are deviations with $f > f_{rotation}$. If there is a lot of unroundness, also the second method does not yield the exact eccentricity. However in practice, the results are acceptable.

Remark 2: In case the player is used for Ecc measurements, the minimum requirement for the turntable (including clamping unit) is: < 3.5 mm eccentricity.

6.2.2 Radial Acceleration: RAC (APP method)

RAC is the maximum acceleration of the radial track deviations in the frequency range up to 500 Hz.

RAD_ACC is the AC-coupled (< 1 Hz) and 500 Hz low-pass filtered radial tracking servo drive signal, compensated for the servo system and converted in such away that it represents the acceleration of the track (see A.1.1 and C.6). A scaling function is applied to get a result in m/sec^2.

$$RAC = \text{scaling_function}\{ MAX \left| (RAD_ACC) \right| \}$$

6.2.3 Radial Noise: RN (APP method).

According to the Red Book, Radial Noise (RN) is the RMS value (integration time-constant 20 msec) of the residual radial tracking error signal in the frequency range from 500 Hz to 10 kHz, measured in a closed loop situation with a servo bandwidth of 200 Hz (f_0 = 200 Hz, c = 3).

Because a servo bandwidth of 200 Hz can cause track following problems, the measurement is executed with a higher servo bandwidth, but the results shall be compensated for this higher bandwidth (see A.1.1 and C.6).

A further problem that influences the RN measurement is the low-frequency content of the HF signal (especially in "fixed EFM-patterns", such as digital silence). Therefore it has become common practice to measure the RN in a limited bandwidth up to 2.5 kHz.

RN_{raw} is the 500 Hz high-pass filtered and 2.5 kHz low-pass filtered residual Push-pull error signal, compensated for the servo system and converted in such away that it represents the displacement of the track (see A.1.1 and C.6).
The peaks in the RN_{raw} signal can be assumed to be < the value corresponding to 300 nm track displacement (this is equivalent to a Crest factor < 10 relative to 30 nm RMS).
A scaling function is applied to get the results in nm.

$$RN_{25} = \text{scaling_function}\{ MAX [RMS(RN_{raw})] \}$$

To ensure that the specification method of the Red Book is fulfilled, it is possible to measure with a 10 kHz bandwidth, however such a measurement should only be executed in a disc area with "random EFM patterns" (e.g. real music).

$$RN = \text{scaling_function}\{ MAX [RMS(RN_{raw,10kHz})] \}$$

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6.2.4 Vertical Deviation Peak: VD_{peak} (APP method)

The Vertical Deviation Peak (VD_{peak}) is the peak value of the vertical track deviations relative to a reference information plane, measured in the frequency range from DC to 500 Hz.

> VD_{raw} is the 500 Hz low-pass filtered focusing servo drive signal, compensated for the servo system and converted in such away that it represents the displacement of the track (see A.1.1 and C.7).
> VD_{ref} is the focusing servo drive signal, measured with a special glass-disc, which defines the reference information plane (thickness 1.20 ± 0.005 mm, refractive index 1.55).
> A scaling function is applied to get the results in mm.

$$VD_{peak} = \text{scaling_function}\{\text{MAX}\left|\left(VD_{raw} - VD_{ref}\right)\right|\}$$

If the positive and negative values of VD_{peak} are measured separately, then the modulus operation shall not be applied and the sign is positive in case of increasing distance between pick-up and disc.

$$VD_{peak,pos} = \text{scaling_function}\{\text{MAX}\left(VD_{raw} - VD_{ref}\right)\}$$

$$VD_{peak,neg} = \text{scaling_function}\{\text{MIN}\left(VD_{raw} - VD_{ref}\right)\}$$

6.2.5 Vertical Deviation RMS: VD_{RMS} (APP method)

The Vertical Deviation RMS (VD_{RMS}) is defined as the RMS value (integration time-constant 2 sec) of the vertical track deviations relative to a reference information plane, measured in the frequency range from DC to 500 Hz.
The peaks in the VD_{raw} signal can be assumed to be < the value corresponding to 1.0 mm vertical displacement (this is equivalent to a Crest factor < 2.5 relative to 0.4 mm RMS).

$$VD_{RMS} = \text{scaling_function}\{\text{MAX}[\text{RMS}\left(VD_{raw} - VD_{ref}\right)]\}$$

6.2.6 Vertical Acceleration: VAC (APP method)

VAC is the maximum acceleration of the vertical track deviations relative to a reference information plane, in the frequency range up to 500 Hz.

> VER_ACC is the AC-coupled (< 1 Hz) and 500 Hz low-pass filtered focusing servo drive signal, compensated for the servo system and converted in such away that it represents the acceleration of the track (see A.1.1 and C.7). A scaling function is applied to get a result in m/sec^2.

$$VAC = \text{scaling_function}\{\text{MAX}\left|\left(\text{VER_ACC}\right)\right|\}$$

6.2.7 Vertical Noise: VN (APP method)

The Vertical Noise (VN) is defined (in extension to the Red Book and IEC 908) as the peak-peak value of the vertical track deviations relative to a reference information plane, in the frequency range 500 Hz to 2.5 kHz.

VN_{raw} is the absolute value of the 500 Hz high-pass filtered and 2.5 kHz low-pass filtered focusing servo drive signal, compensated for the servo system and converted in such away that it represents the displacement of the track (see A.1.1 and C.7). A scaling function is applied to get the results in μm.

$$VN = \text{scaling_function}\{\text{MAX}\left|\left(VN_{raw}\right)\right|\}$$

6.3 Main channel errors (CP method)

E11, E21, E31, E12, E22, E32, BLER, BERL, C2_BERL, UNCORR
Subcode Q-channel Errors: SCQER
Subcode R..W channel Errors: PAER, PANG

In addition to the Red Book the following definitions are used:

Exy: (e.g. E11, E21, ..) is defined as the number of frames per second, in which decoder y (C1, C2 decoder) has detected x erroneous symbols.

E3y: is defined as the number of frames per second, in which decoder y (C1, C2 decoder) has detected 3 or more erroneous symbols.

BLER: (BLock Error Rate) is defined as the number of frames, in which decoder C1 has detected 1 or more erroneous symbols (E11+E21+E31), divided by the total number of frames that has been processed.
BLER shall be measured per second (BLER_1). Every second a sliding average over 10 seconds (BLER_10) is calculated, based on the BLER_1 values of the last 10 seconds.

BERL: (Burst ERror Length) is defined as the number of successive frames leaving the C1 decoder, in which 2 or more erroneous symbols have been detected (E21+E31).

C2_BERL: is defined as the number of successive frames leaving the C2 decoder, in which 2 or more erroneous symbols have been detected (E22+E32).

UNCORR: is the number of frames leaving the C2 decoder that are uncorrectable and have to be interpolated (E32).
This gives some estimation about noticeable clicks (audio signal interpolation problems).

SCQER: is defined as the number of subcode Q-channel blocks per second, having CRC errors.

PAER: is defined as the number of PACK blocks per second in the subcode channels R-W, having errors.

PANG: is defined as the number of uncorrectable PACK blocks per second.

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6.3.1 Main channel errors: considerations and recommendations

Although discs with BLER values much lower than the maximum allowed can easily be produced, BLER values of 3.10^{-2} (= 220 counts per second) are not disastrous. As long as the errors are small and randomly scattered over the disc, the CIRC error correction system is powerful enough to correct much higher error rates than 3.10^{-2}.

However: A low BLER value of a maiden disc, leaves more margin for damages at the end-user.

What does reduce the correcting capabilities rather fast, are "burst errors". Therefore limits are specified for the size of and the distance between local defects like air bubbles and black spots on a maiden disc. A defect of a size of 300 μm is causing about half of the C2 frames within an interleave length to contain single errors.

The remaining capacity of the C2 corrector is needed for handling random errors, that will always be present and for additional damages that will occur at the end-user.
Therefore there should not be another defect within a distance of 20 mm, which corresponds to an interleave length of CIRC.

Nowadays CIRC decoders are more powerful than the single error correcting ones as specified in the Red Book, and in practice nearly every decoder has double correcting capabilities (and some even quadruple) for as well the C1 as the C2 decoder. This means that much bigger defects can be handled than specified in the Red Book.

However: Also the servo systems will suffer from bigger defects, which is a reason to stick to the existing specifications.

As a consequence of this, the number and size of errors that could be allowed on a disc can be applied in a flexible way. Each manufacturer can design his own quality rules defining the limits to be applied for the measurement of the errors in the decoded signals.

For the CD-RMS the following requirements for measuring the decoded signals apply:
To exclude the small and random read-out imperfections (caused by MTF and ISI effects, which are covered by the jitter measurement), the decoded signals are measured after MTF correction.

In this way the BLER, etc. are more a measure for the "contamination" of the disc, while the jitter (measured without MTF correction) is more a measure for the "pit-structure" on the disc.

The error-correction strategy should be such, that per decoder unit (C1 & C2) two symbols per frame can be corrected.

6.4 Optical measurements

Several optical measurements can only be executed on specialized optical measuring set-ups. Also for these measurements it is better to follow standardized measuring procedures to guarantee the necessary repeatability and reproducibility.

6.4.1 Birefringence measuring method

6.4.1.1 Principle of measurement

In order to measure the birefringence, circular polarized light in a parallel beam is irradiated on to the disc to be measured. The phase retardation is measured by observing the ellipticity of the reflected light.

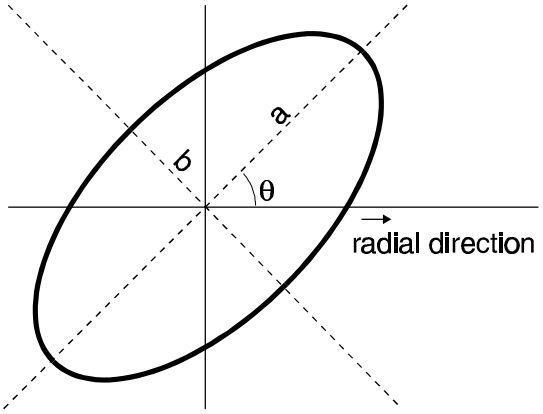

Figure 12 Ellipse with ellipticity e = b/a and orientation q

The orientation θ of the ellipse is determined by the orientation of the optical axis:

$$\theta = \gamma - \pi / 4 \qquad (1)$$

in which γ is the angle between the optical axis and the radial direction.

The ellipticity e = b/a is determined by the phase retardation δ as:

$$e = \tan\left(\frac{\pi / 2 - \delta}{2}\right) \qquad (2)$$

When the phase retardation δ is known, the birefringence BR can be expressed as a fraction of the wavelength:

$$BR = \frac{\lambda}{2.\pi}.\delta \qquad (3)$$

So, by observing the elliptically polarized light reflected from the disc, not only the birefringence value can be measured (specification BR = 100 nm max, see Red Book page 3), but also the orientation of the optical axis in the substrate can be analyzed.

6.4.1.2 Measurement conditions

mode of measurement	in reflection, double pass through the substrate
wavelength of laser light:	$\lambda = 785 \pm 20$ nm
beam diameter:	$\varnothing = 1.0 \pm 0.2$ mm
angle of incidence:	$\beta = 7.0 \pm 0.2$ ° in radial direction
clamping:	Disc fixed between two concentric rings ($\varnothing_{min}$ = 29 mm, $\varnothing_{max}$ = 31 mm), with a clamping force 1.5 N < F_1 < 2 N.
chucking:	The chucking force F_2 shall be < 0.5 N (see Figure 13)

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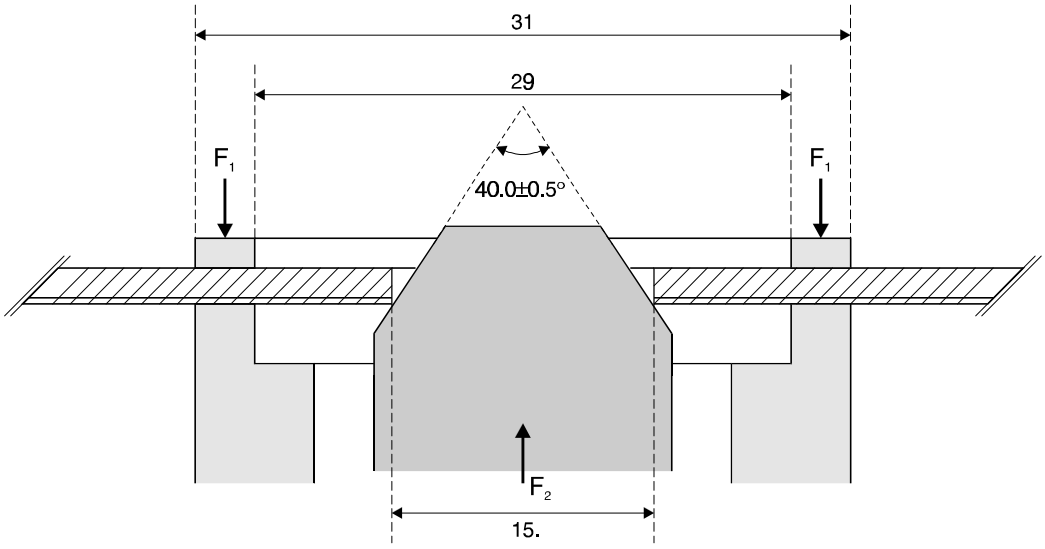

Figure 13 Clamping and chucking

disc mounting:	horizontal
disc linear velocity:	1.2 m/sec
ambient temperature *:	23 ± 2 °C
relative humidity *:	50 ± 5 %
electrical filtering:	low-pass filter with –3 dB cut-off frequency 20 Hz (first order integrator with timeconstant 8 msec)

Birefringence can show locally big variations. To guarantee sufficient radial resolution it is recommended to keep the step size in radial direction ≤ 0.25 mm.

* If necessary, a recovery time for the disc must be allowed.

6.4.1.3 Example of measurement set-up

A schematic drawing of a measurement set-up is given in the following figure.

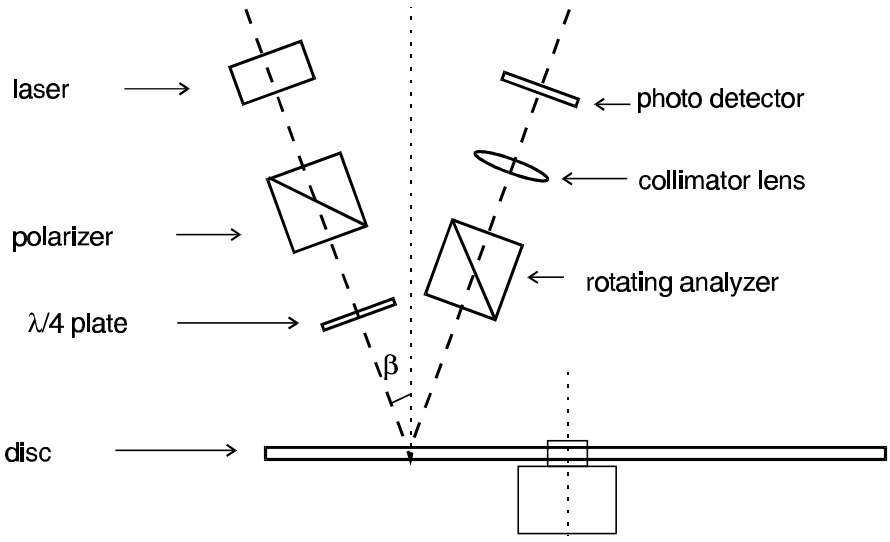

Figure 14 Example of birefringence measuring set-up

Light from a laser source, collimated into a parallel beam passes through a polarizer (extinction ratio $\approx 10^{-5}$) and is made circular by a $\lambda/4$ plate. The ellipticity of the reflected light is analyzed by a single rotating analyzer and photo detector. For every location on the disc, minimum and maximum intensity values are measured and the ellipticity can be calculated as:

$$e^2 = \frac{I_{min}}{I_{max}} \qquad (4)$$

Combining (2), (3) and (4) yields:

$$BR = \frac{\lambda}{4} - \frac{\lambda}{\pi} * \arctan\left(\sqrt{\frac{I_{min}}{I_{max}}}\right) \qquad (5)$$

This set-up can be easily calibrated as follows:
- I_{min} is set to zero by measuring a polarizer or a $\lambda/4$ plate
- $I_{min} = I_{max}$ when measuring a mirror.
- Front surface reflection can be eliminated by off-setting the detector output by the correct amount.

6.4.1.4 Interchangebility of measuring results

Various other measuring methods are possible and allowed as long as the measurement conditions stated in section 6.4.1.2 are obeyed. In order to guarantee Interchangebility of measuring results, the following guidelines must be followed:

(1) The angle of incidence determines the amount of vertical birefringence, that is measured in addition to the in-plane birefringence. It is therefore important to control the angle of incidence very accurately.

(2) In the measurement method that is used, the orientation of the optical axis in the plane of the substrate has to be taken into account. No assumptions can be made on the orientation of the optical axis.

(3) When analyzing the reflected light, the light reflected by the substrate front surface must be taken into account.
Apart from the front surface reflection, AC components may occur due to interference of the reflections from the front surface with the reflections from the information layer. This AC reflectance effect is only significant if the disc substrate has an extremely high degree of plan-parallelism and the degree light source has a high degree of coherence.

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6.4.2 Reflectivity measuring methods

The reflectivity of a disc can be determined in several ways. The basic measuring method is using the "Ulbricht sphere" as specified in the Red Book. In this method all the light reflected from the disc, so also the randomly scattered portion, is measured.
This method however is not very practical.

In practice use is made of the reflected light falling into the objective lens of the pick-up unit of a CD player focused on the disc. The reflectivity of the disc under investigation (DUI) can be determined by comparing the amount of light on the photo detectors coming from the DUI, to the amount of light on the photo detectors coming from a reference disc (RD). When the reflectivity of the RD is known, the reflectivity of the DUI can easily be calculated.
(see 6.1.1)

6.4.2.1 Parallel vs. Focused calibration

The reflectivity of the RD can be specified in 2 ways:
- as parallel reflectivity,
- or as focused reflectivity.

The following figure shows how the parallel reflectivity is determined:

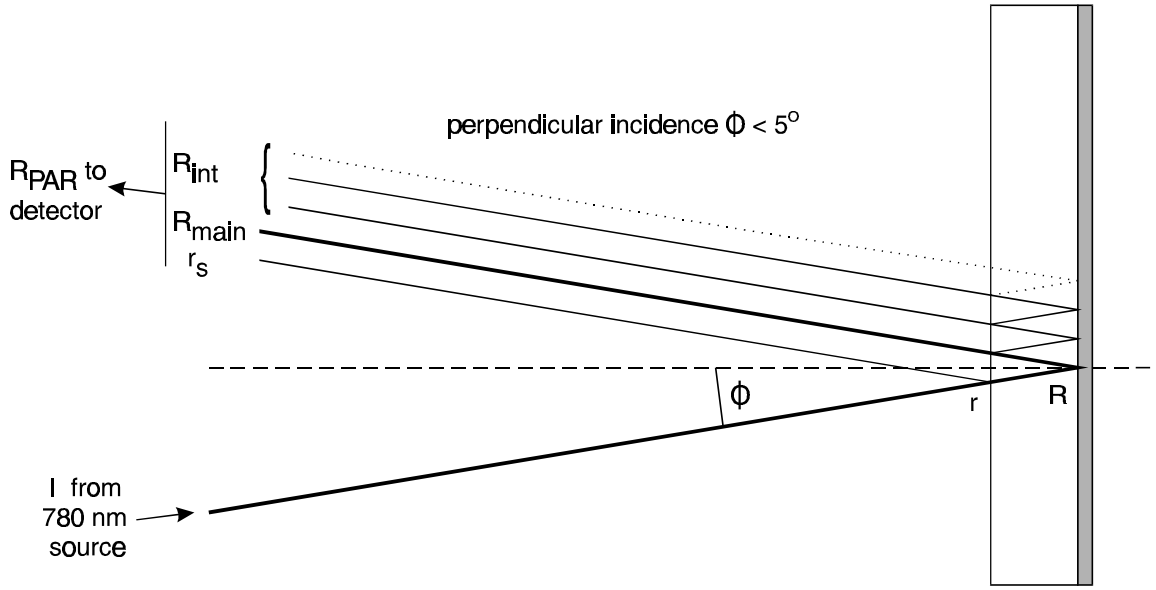

Figure 15 Schematic set-up for calibration of the reference disc

In this figure the following applies:

R	=	reflectivity of the reflective layer (including the double pass substrate transmission)
r	=	reflectivity of the air-substrate interface
I	=	incident beam
r_s	=	reflectance caused by the reflectivity of the air-substrate interface
R_{main}	=	main reflectance caused by the reflectivity of the reflective layer
R_{int}	=	parasitic reflectances from inside the disc substrate
R_{PAR}	=	total measured parallel reflectance = $r_s + R_{main} + R_{int}$

When measured with the pick-up unit of a CD player, only the light returned by the reflective layer of the disc (R_{main}) will fall inside the objective lens. The reflected light coming from the front surface of the disc and the light coming from the parasitic reflectances inside the disc will mainly fall outside the objective lens:

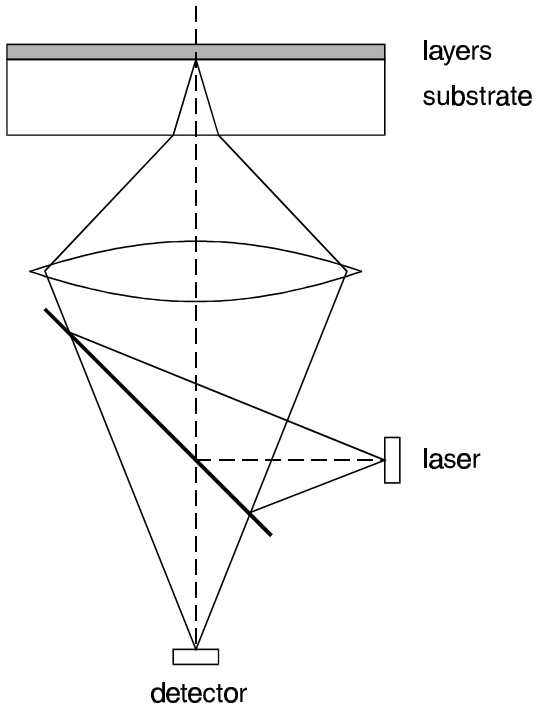

Figure 16 Schematic set-up for reflectivity measurements

The "main" reflectance from the reflective layer, entering the objective lens, can be calculated as follows:

$$R_{main} = \frac{(1-r)^2 * (R_{PAR} - r)}{1 - r * (2 - R_{PAR})}$$

in which r is the air-substrate interface reflectivity:

$$r = \left(\frac{n-1}{n+1}\right)^2$$

in which n is the refractive index of the substrate.

One should realize that the reflectivity measured in this way is not only depending on the reflectivity itself, but is also influenced by the shape and depth of the pits and the shape of the light spot. Therefore this way of measuring is more relevant for the CD system than measuring with the "Ulbricht sphere". To minimize the influence of birefringence effects, non-polarizing optics shall be used.

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6.4.2.2 Reference disc

For calibration a reference disc is needed that does not suffer from birefringence and is independent of pit/player parameters. A good stable reference disc can be made according to the following specifications:

- glass substrate, thickness = 1.200 mm, index of refraction = 1.55, double pass absorption < 1 %
- Au reflecting layer, thickness > 100 nm, protective lacquer on top

Produced under optimum conditions a value for R_{PAR} > 96% can be reached.
This corresponds to R_{main} > 87%.

6.4.2.3 Measuring procedure

The measuring itself now is very simple:

1) with the reference disc in the player, the top signal level from the photo detector diodes is measured: V_{REF} (arbitrary units)
2) with the disc under investigation in the player, also the top signal level of the photo detector diodes is measured: V_X (same arbitrary units)
3) calculate: $R_X = \frac{V_X}{V_{REF}} * R_{REF}$ (R_{REF} is the reflectivity value of the reference disc)

6.4.2.4 Alternative reflectivity specifications

The value of the reflectivity is influenced by the measuring method.
With the Ulbricht sphere all the light reflected from the disc, including the scattered light, is measured.
With the parallel beam method, the light scattered by e.g. the pits is not detected, so a lower value is measured.
With the focused beam method also the parasitic reflectances caused by the air-substrate interface are excluded, causing a further reduced value.

Now, the reflectivity value R_{REF} of the reference disc can be specified in 3 different ways: as "Ulbricht" value, as parallel value or as focused value.
All 3 methods, which are equivalent but result in different values, can be used to specify the reflectivity of the disc under investigation:

measuring method	specified value of reference disc	specification for the disc under investigation
Ulbricht	---	R_X > 70 %
focused	parallel ($R_{REF} = R_{PAR}$)	$R_{X\text{-}par}$ > 65 %
focused	focused ($R_{REF} = R_{main}$)	$R_{X\text{-}foc}$ > 58 %

6.5 Dimensions and sundries (GP method)

6.5.1 Diameters

Lead-in Start Diameter, Program Start Diameter, Program End Diameter and Lead-out End Diameter can be measured in different ways:

- by means of an optical measuring microscope, which method can easily result in an accuracy of ± 20 μm.
- by means of position sensors on the radial tracking system of a CD-RMS. In this case the measuring accuracy may be less, but should be better than ± 50 μm.

On a CD-RMS the following procedures could be applied to determine the diameters. During the measurement the radial tracking system is held at the related position by jumping back one track each revolution. The average position of the objective lens relative to the sledge during this "jump mode" should be accurately controlled (dc-offset must be small enough).
The eccentricity of the turntable (including the clamping unit) shall be < 3.5 μm.

1) The Lead-in Start Diameter is twice the average radial position of the sledge at the first revolution during which an HF/EFM signal according to the Red Book specification is detected.
2) The Program Start Diameter is twice the average radial position of the sledge at the first revolution during which the first subcode Q is detected that indicates the Program Area (first track ≠ 00, index = 00).
3) The Program End Diameter is twice the average radial position of the sledge at the first revolution during which the first subcode Q is detected that indicates the Lead-out Area (track AA, index 01).
4) The Lead-out End Diameter is the twice the average radial position of the sledge at the first revolution during which the HF/EFM signal stops fulfilling the Red Book specifications.

6.5.2 Scanning velocity (GP method)

The average scanning velocity may be calculated by measuring the time per one or more complete revolutions of the CD (see AAP method 5.3.2) and the actual tracking radius.

6.5.3 Average track pitch (GP method)

The average track pitch may be calculated by counting a fixed number of CD revolutions in relation to the signal of a radial position sensor. Because of the low resolution of radial position sensors (in relation to the track pitch), it can take several seconds to get the data. The data shall be addressed as:

ATIME = (measurement start ATIME + measurement end ATIME) / 2

6.5.4 Skew of the disc surface and tilt of the reflected beam

Skew of the disc surface and tilt of the reflected beam can not easily be measured on a player type of measuring set-up. Therefore special optical measuring equipment is needed to perform these measurements (to be defined in future).
(skew = angular deviation of the beam incident surface from the reference plane)
(tilt = angular deviation of the reflected beam in the radial direction from the normal line of the reference plane)

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7 Qualification

It is recommended that each newly designed or redesigned CD-RMS (or a "Reference Player" component) is offered to Philips for qualification. If approved, the design will receive a certificate of approval.

8 Calibration (at the end-user of a CD-RMS)

It is highly recommended to supply a set of "reference discs" with every player. These discs have to be measured on the player before the player and the discs are shipped to the end-user. At the end-user, the measuring results of the "reference discs" have to be the same as before shipment at the manufacturer's site.

At regular time intervals the system shall be re-calibrated with the "reference discs".
Because the amount of work and mathematics involved with multi-point calibration, it is highly recommended that the CD-RMS in equipped with a built-in automatic calibration procedure (preferably according to linear regression conditions). The system has to indicate, if a parameter cannot be calibrated in accordance to the accuracy specified for the CD-RMS.

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Annex A SERVO SYSTEM DEFINITIONS

A.1 General Servo Model

In the **CD Reference Measuring System** (CD-RMS) several servo systems have to be specified. For this purpose the following general servo model is used.
It is assumed that a real servo will be realized in such away, that it satisfies this general servo model as good as possible. Secondary order effects and parasitic resonances should be avoided or compensated.

Because electro-mechanical actuators mostly convert a current into a force, their simplest form can be modeled by a double integration when we want to consider the position or displacement as a result of that force. (see C.9 + C.10)

acceleration: $a(t) = \frac{F(t)}{m} = \frac{k * I(t)}{m}$

velocity: $v(t) = \int a(t).dt + v_0$

position: $y(t) = \int v(t).dt + y_0$

Therefore we can state for the **actuator**:

$$H_3(j\omega) = \frac{\omega_0^2}{(j\omega)^2}$$

ω_0 is the radial frequency where $|H_3(j\omega_0)| = 1$.

The **position detector** is mostly frequency independent. Suppose:

$$H_1(j\omega) = 1$$

For stability reasons such a system has to be compensated by a **lead/lag network**, which transfers the 2nd order roll-off into a 1st order roll-off at the point where the open loop transfer curve crosses the 0 dB axis:

$$H_2(j\omega) = \frac{1}{c} * \frac{1 + j.\frac{\omega}{\omega_0 / c}}{1 + j.\frac{\omega}{\omega_0 * c}}$$

$|H_2(j\omega_0)| = 1$; c determines the phase margin.

A good compromise is c = 3, giving a phase margin of 53°.

The total open loop transfer function is now given by (see C.11):

$$H(j\omega) = \frac{-1}{c} * \frac{\omega_0^2}{\omega^2} * \frac{1 + j.\frac{\omega}{\omega_0 / c}}{1 + j.\frac{\omega}{\omega_0 * c}}$$

In this relation ω_0 is the frequency where the total open loop gain crosses the 0 dB axis:

$$|H(j\omega_0)| = 1.$$

This usually corresponds roughly with the bandwidth of the closed loop system.

The closed loop gain is: $H_{cl} = \frac{H}{1+H}$

With the Laplace operator p = j.ω, this can be written in the following form:

$$H_{cl} = \frac{1 + c.\frac{p}{\omega_0}}{1 + c.(\frac{p}{\omega_0}) + c.(\frac{p}{\omega_0})^2 + (\frac{p}{\omega_0})^3}$$

$$= \frac{1 + c.\frac{p}{\omega_0}}{\left(1 + \frac{p}{\omega_0}\right) * \left(1 + (c-1).(\frac{p}{\omega_0}) + (\frac{p}{\omega_0})^2\right)}$$

For the closed loop we can derive the following relations:

$$\frac{Y(j\omega)}{X(j\omega)} = \frac{H(j\omega)}{1+H(j\omega)}$$

and

$$E(j\omega) = X(j\omega) - Y(j\omega) = \frac{X(j\omega)}{1+H(j\omega)} = \text{ tracking error}$$

For the focus servo the tracking error has to be smaller than the focal depth ($\lambda / 2NA^2$).

For the radial servo, the tracking error has to be smaller than 1/4 of the track pitch.

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A.1.1 Trackability of sinusoidal variations

When we suppose a sinusoidal position deviation or displacement:

$$x(t) = X_{max} * \cos(\omega t)$$

then: $a(t) = \frac{d^2x(t)}{dt^2} = -\omega^2 * X_{max} * \cos(\omega t)$

so: $|A_{max}| = \omega^2 * |X_{max}|$

Suppose E_{max} is the maximum allowed tracking error.
From the foregoing equations we can derive:

The maximum allowable displacement for single frequencies is

$$X_{max}(\omega) < E_{max} * |1 + H(j\omega)|$$

see C.12:

$$\text{for } \omega << \omega_0 : \; X_{max}(\omega) < \frac{1}{c} * \frac{\omega_0^2}{\omega^2} * E_{max}$$

$$\text{for } \omega >> \omega_0 : \; X_{max}(\omega) < E_{max}$$

The maximum allowable acceleration for single frequencies is

$$A_{max}(\omega) < \omega^2 * E_{max} * |1 + H(j\omega)|$$

see C.12:

$$\text{for } \omega << \omega_0 : \; A_{max}(\omega) < \frac{1}{c} * \omega_0^2 * E_{max}$$

$$\text{for } \omega >> \omega_0 : \; A_{max}(\omega) < \omega^2 * E_{max}$$

When we know the values for E_{max}, X_{max} and A_{max}, we can calculate the minimum needed bandwidth for the different servo systems.

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A.1.2 Compensations for a standard servo

To get compatible measurement results it is needed to specify a "standard" servo. This is a servo with a defined transfer function (f_0 and c).
However in reality we sometimes need an actual servo system with characteristics differing from the standard. To get still compatible measurement results with such a servo, we must compensate the error signals for the differences.

A player with an actual servo (H_a) can be adapted in several ways (see C.13, C.14 and C.15), to give measurement results compatible with the standard servo (H_s).

The system set-up of C.13 completely transfers the actual system into a standard servo, which often is not possible.

The system of C.14 gives a good set-up for measuring purposes.
It has 1 disadvantage: it needs a separate position detector.
To derive the acceleration from X, the signal has to be differentiated twice.

The system of C.15 has the problem that mostly the displacement signal Y is not directly available as an electrical signal. What often is available, is the current through the actuator, which is a measure for the acceleration (see C.16).

For this signal Z(jω) we can derive:

$$\frac{Z}{X} = \frac{H_1 * H_2}{1 + H_1 * H_2 * H_3} = \frac{1}{H_3} * \frac{H}{1+H}$$

$$\frac{Y}{X} = \frac{H_1 * H_2 * H_3}{1 + H_1 * H_2 * H_3} = \frac{H}{1+H} = H_3 * \frac{Z}{X}$$

From this we see that Y(jω) can be easily derived from Z(jω) by multiplying Z with H_3(jω), where H_3(jω) is a double integration.

The only inaccuracies left over now are caused by the tracking error:

> Y is the displacement of the objective lens and not the displacement X of the disc, which we are interested in. This can rather easily be compensated by multiplying all needed signals by (1+H)/H.

The tracking error E_a(jω) has to be compensated for the standard servo characteristic by multiplying it with $(1+H)/(1+H_s)$.

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A.2 Calculations for the focus servo

Combining the requirements for the vertical deviations and the relation $A_{max} = \omega^2 * X_{max}$ the appropriate curves can be found in C.17.
For the low frequencies (< 22.5 Hz) we see that the limit on the displacement is dominating. For the middle frequencies (22.5 Hz < f < 500 Hz) the requirements for the maximum acceleration are more severe, while for the high frequencies (> 500 Hz) there is only a requirement for the displacement.

The maximum tracking error E_{max} has to be smaller than $\lambda / (2NA^2)$ (Focus depth)
so:

$$E_{max} < \frac{0.78}{2*0.45^2} = 1.9\ \mu m$$

To get sufficient margin, we will calculate with a safety factor of about 5:

$$E_{max} = 0.4\ \mu m$$

The minimum needed bandwidth for the focus servo can now be determined from the acceleration tracking error for frequencies below ω_0 (see also C.12):

$$\omega_0^2 = \frac{c * A_{max}}{E_{max}} \quad \Rightarrow \quad f_0 > 1378\ Hz$$

from the displacement tracking error for frequencies below ω_0 we can derive:

$$X_{max} = \frac{\omega_0^2 * E_{max}}{\omega^2 * c}$$

With the above bandwidth a deviation of 0.5 mm at 22.5 Hz will just result in 0.4 μm tracking error.

A "bended" disc will have deviations at the double rotation frequency, so at the inner side it is reasonable to calculate with this 22.5 Hz.

The chosen bandwidth is rounded off upwards to f_0 = 1500 Hz.

A.3 Calculations for the radial servo

Combining the requirements for the radial deviations and the relation $A_{max} = \omega^2 * X_{max}$ the appropriate curves can be found in C.18.
For the low frequencies (< 12 Hz) we see that the limit on the displacement is dominating. For the middle frequencies (12 Hz < f < 500 Hz) the requirements for the maximum acceleration are more severe, while for the high frequencies (> 500 Hz) there is only a requirement for the displacement.

The maximum tracking error E_{max} has to be less than ¼ of the track pitch so:

$$E_{max} < \frac{1.6}{4} = 0.4\ \mu m$$

To get sufficient margin, we will calculate with a safety factor of about 4:

$$E_{max} = 0.1\ \mu m$$

The minimum needed bandwidth for the radial servo can now be determined from the acceleration tracking error for frequencies below ω_0 (see also C.12):

$$\omega_0^2 = \frac{c * A_{max}}{E_{max}} \quad \Rightarrow \quad f_0 > 551\,Hz$$

from the displacement tracking error for frequencies below ω_0 we can derive:

$$X_{max} = \frac{\omega_0^2 * E_{max}}{\omega^2 * c}$$

With the above bandwidth a deviation of 70 μm at 12 Hz will just result in 0.1 μm tracking error.

A disc with an off-center center hole will have deviations at the rotation frequency, so at the inner side it is reasonable to calculate with this 12 Hz. However when the tracks are elliptical instead of circular, also "eccentricity" with the double rotation frequency will exist. The amplitude of this will mostly be much smaller.

The chosen bandwidth is rounded off upwards to f_0 = 600 Hz.

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Annex B ACCURACY DEFINITIONS

B.1 Example of the accuracy specification

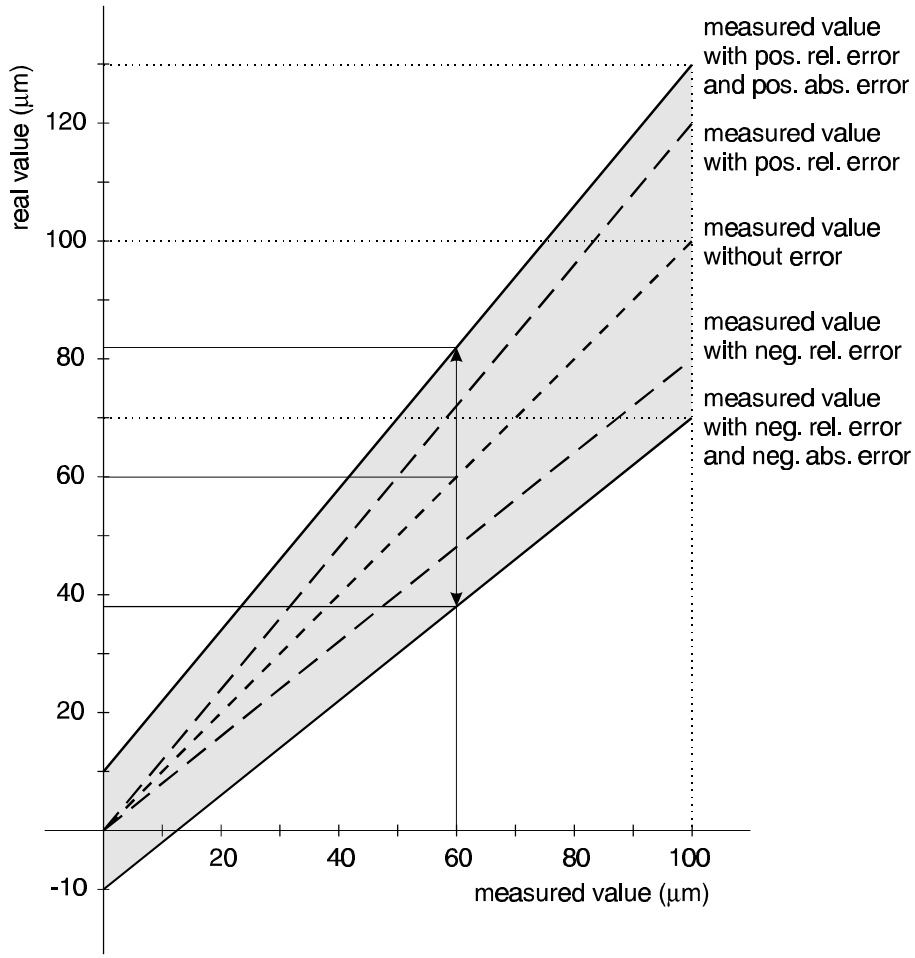

Figure 17 Example of accuracy spec ±20% ±10mm

In this example a measured value of 60 µm means that the real value will be between 38 and 82 µm.

Annex C GENERAL FIGURES

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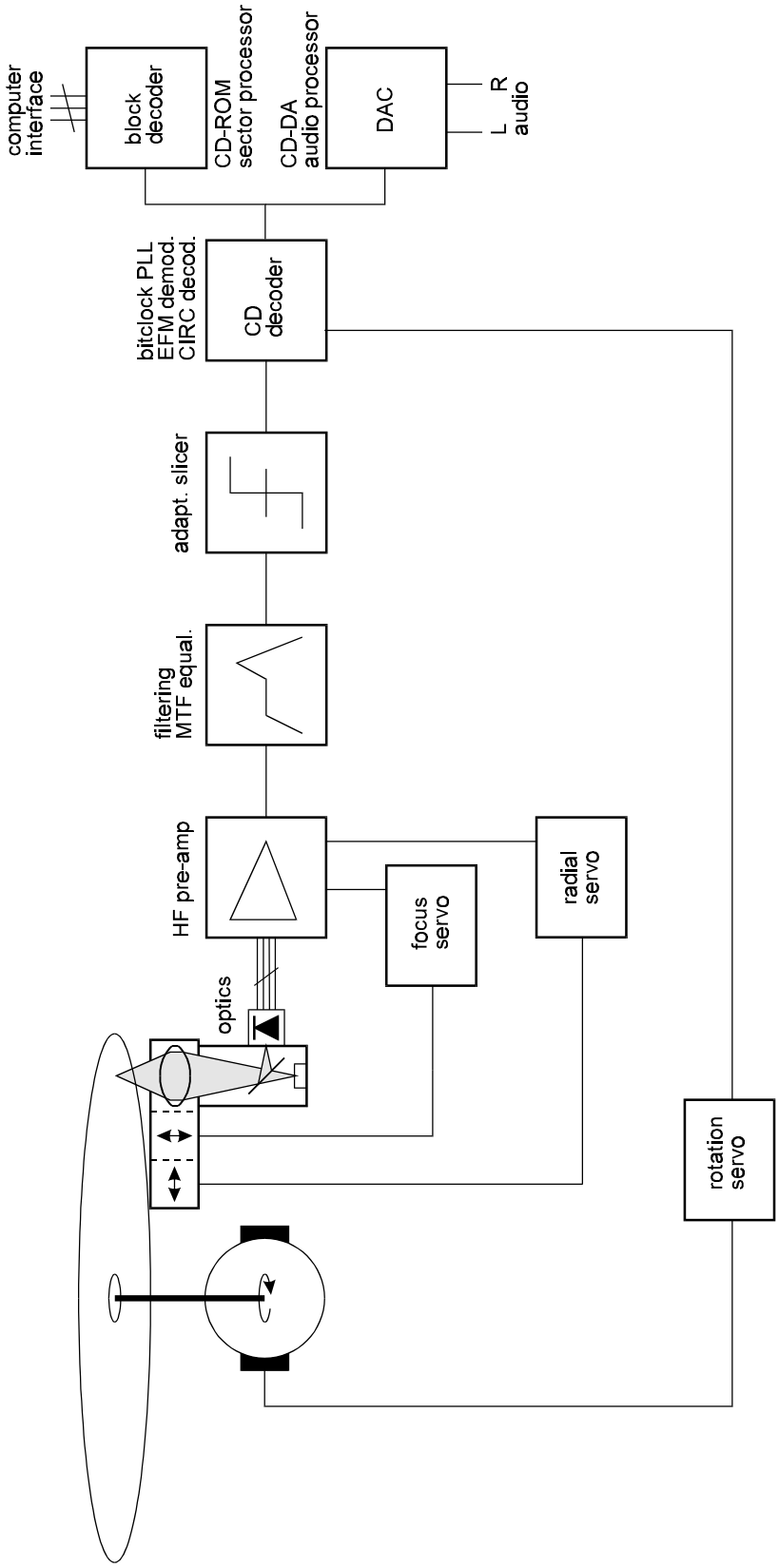
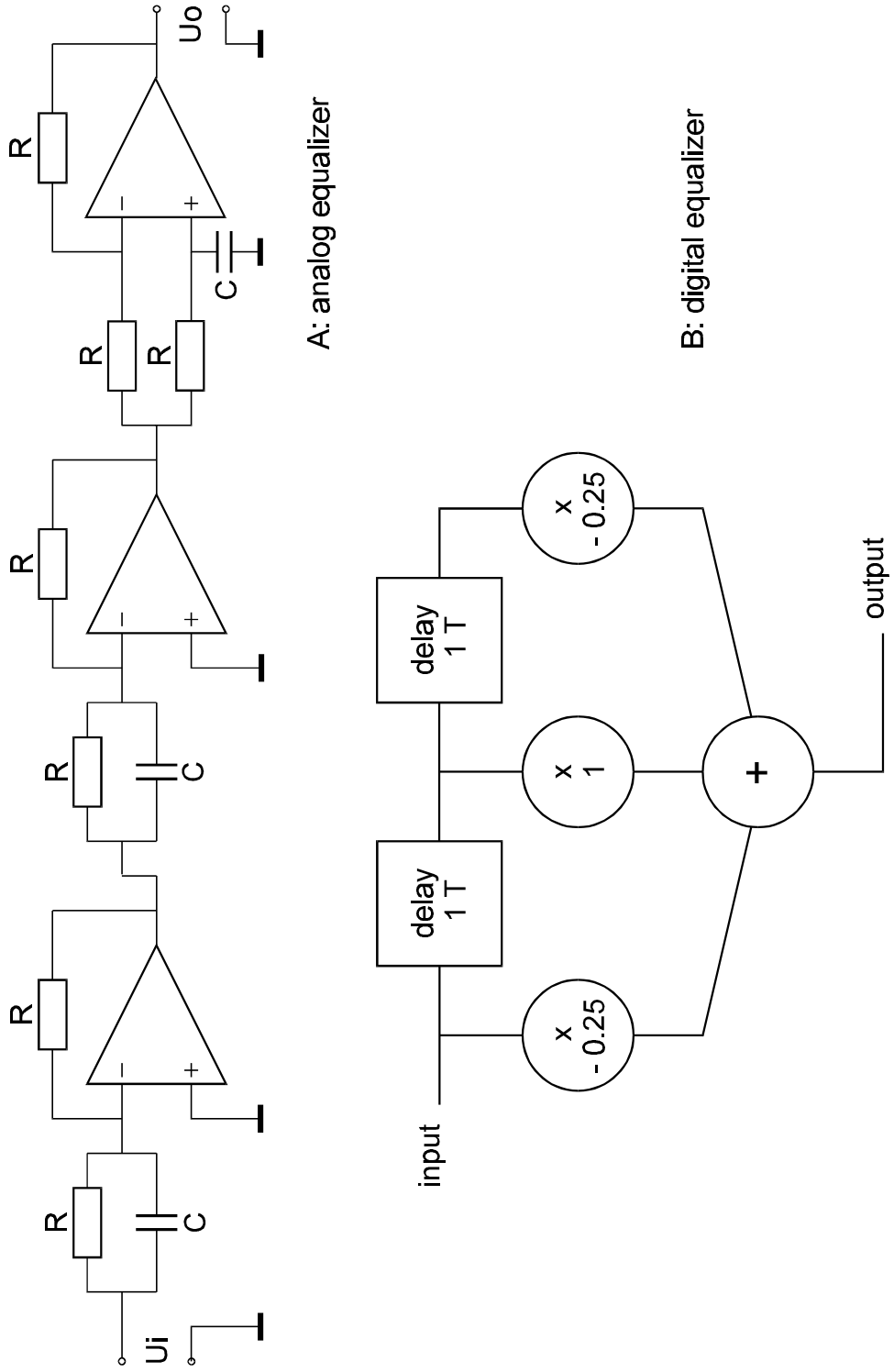
C.1 General CD player block diagram



C.2 Examples of implementation of MTF equalizer



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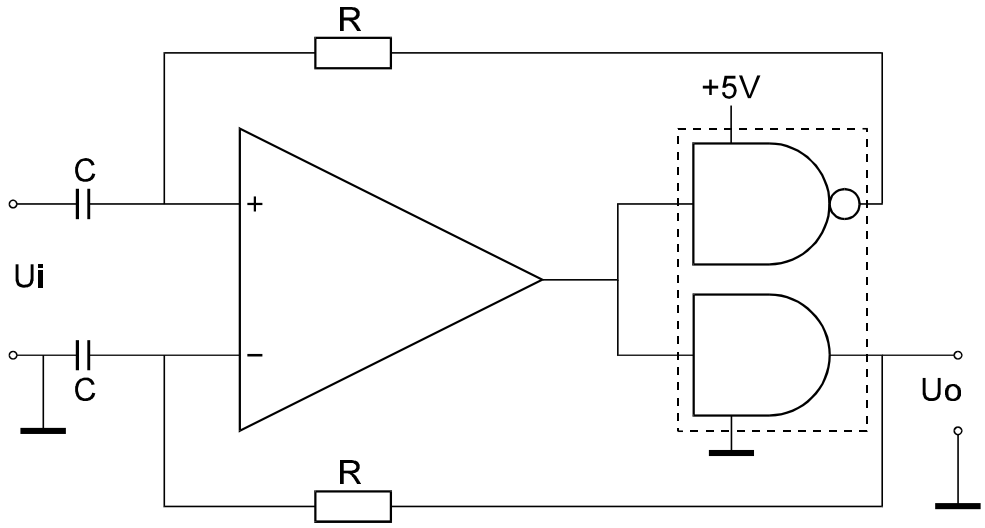
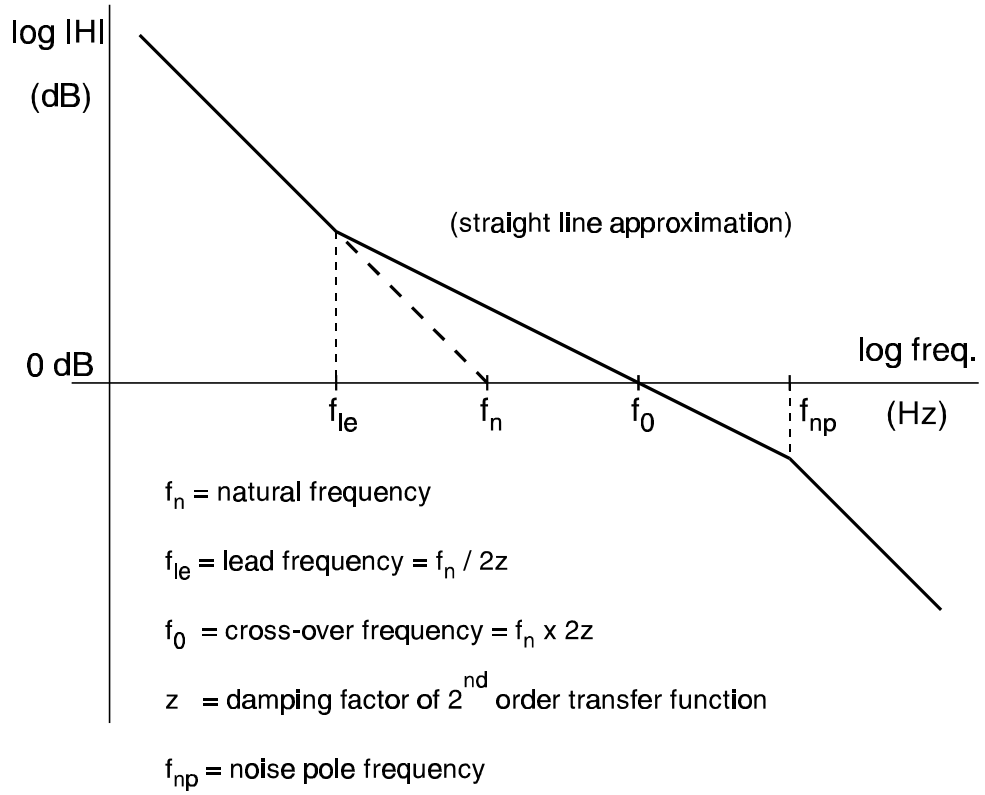
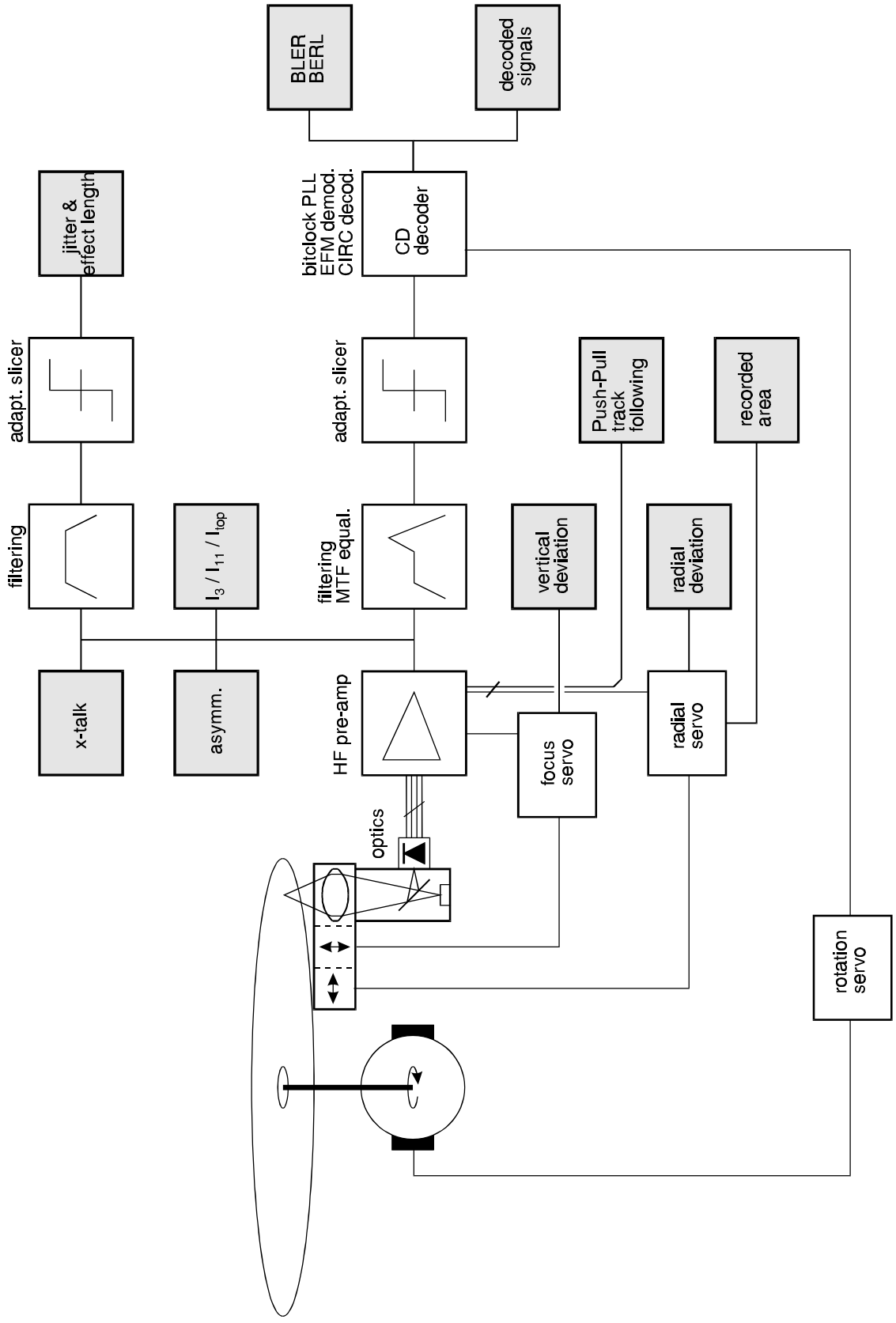
C.3 Example of implementation of Adaptive Slicer



C.4 Amplitude transfer function of PLL system



C.5 CD player block diagram with measuring functions



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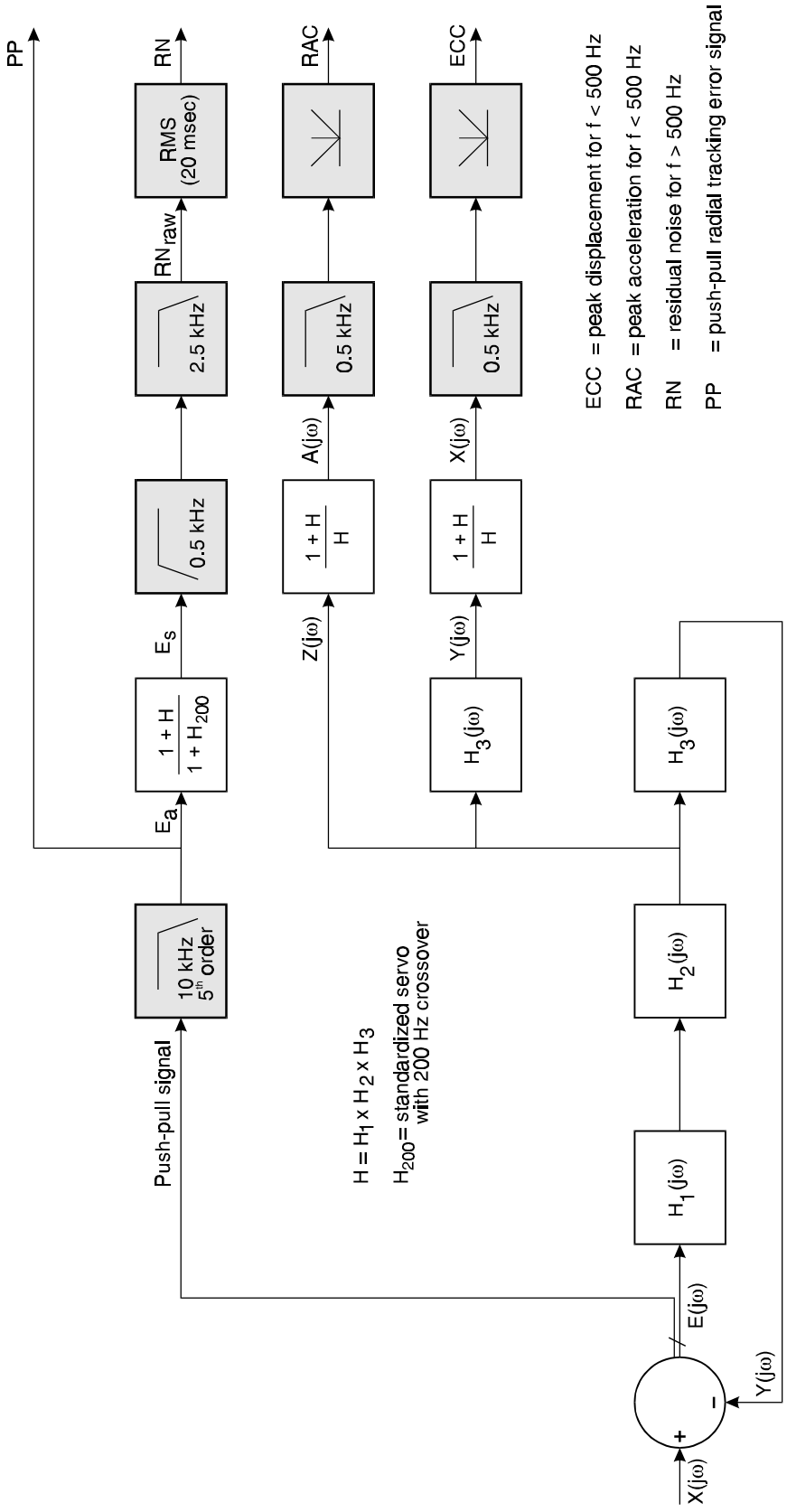
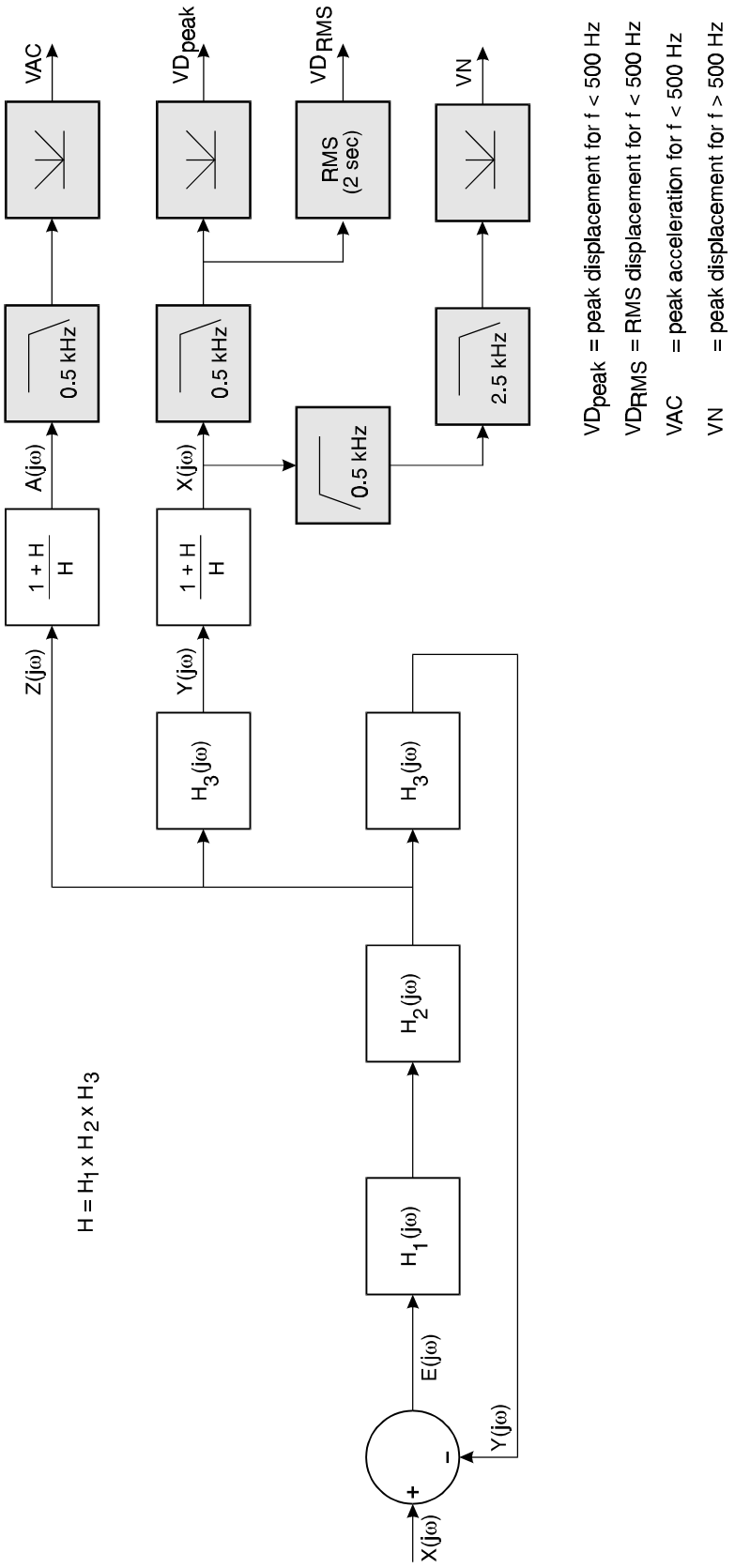
C.6 Measuring circuits and filters for the radial servo



C.7 Measuring circuits and filters for the focus servo



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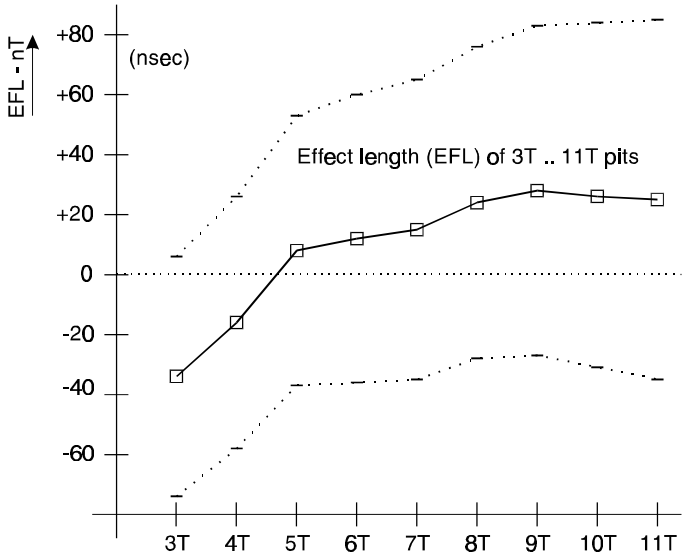
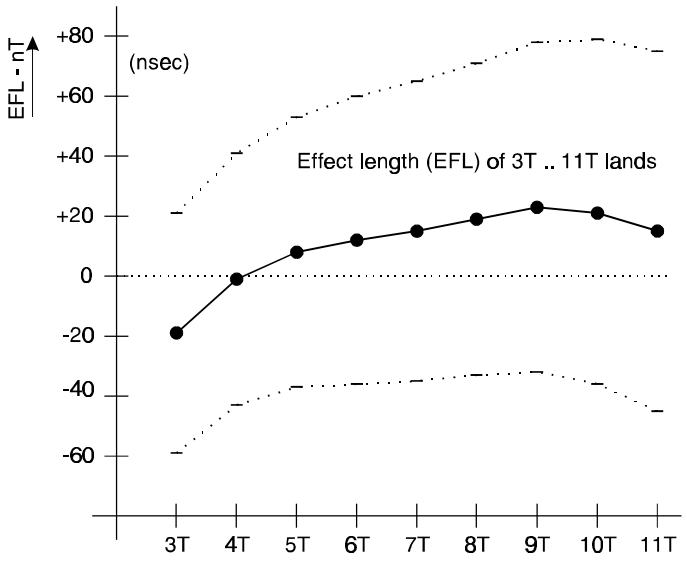
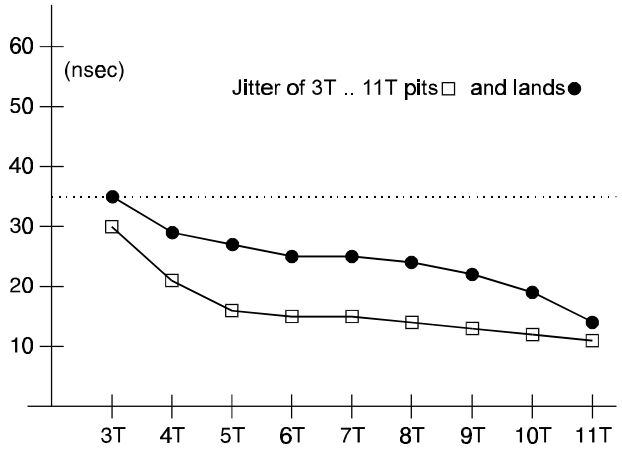
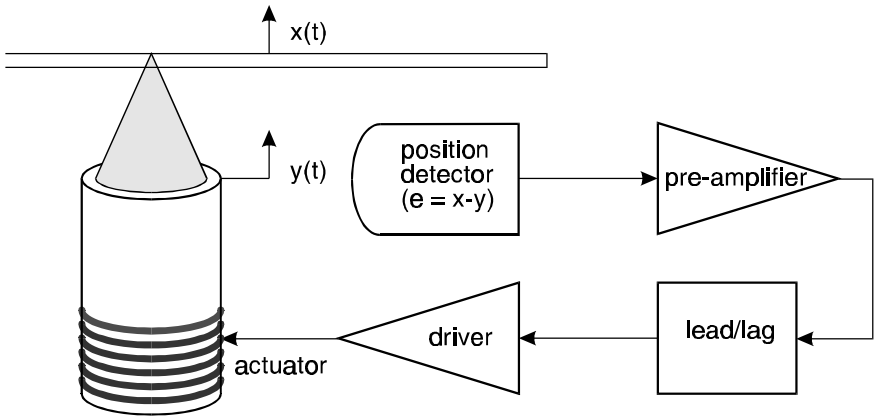
C.8 Examples of Effect Length & Jitter



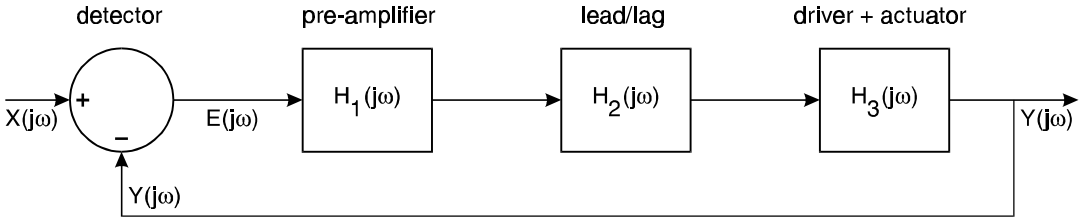




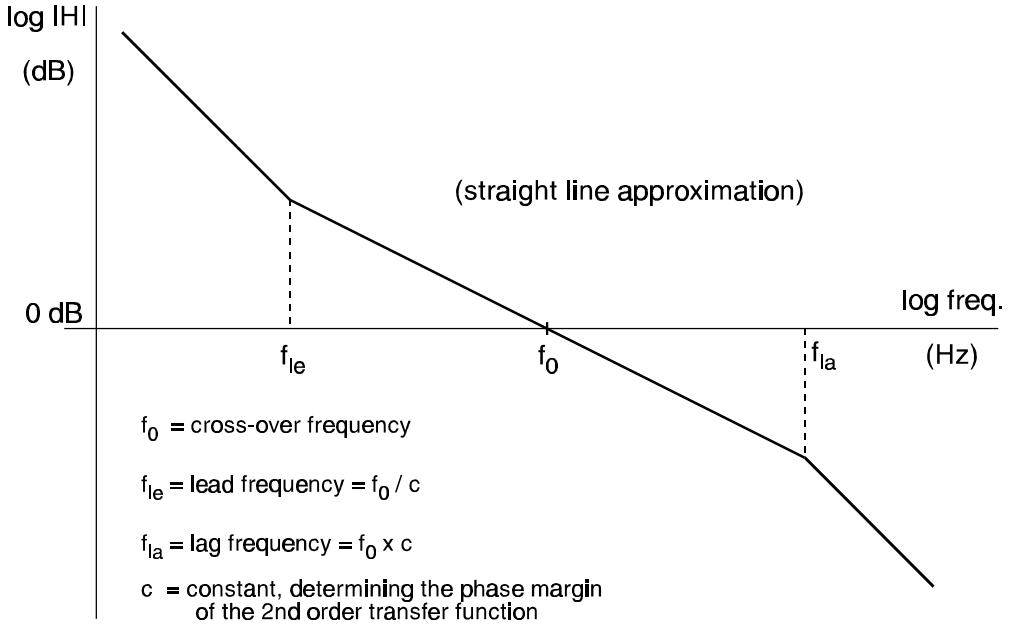
C.9 Example of servo system (focus)



C.10 Electrical model of servo system



C.11 Amplitude transfer function of servo system



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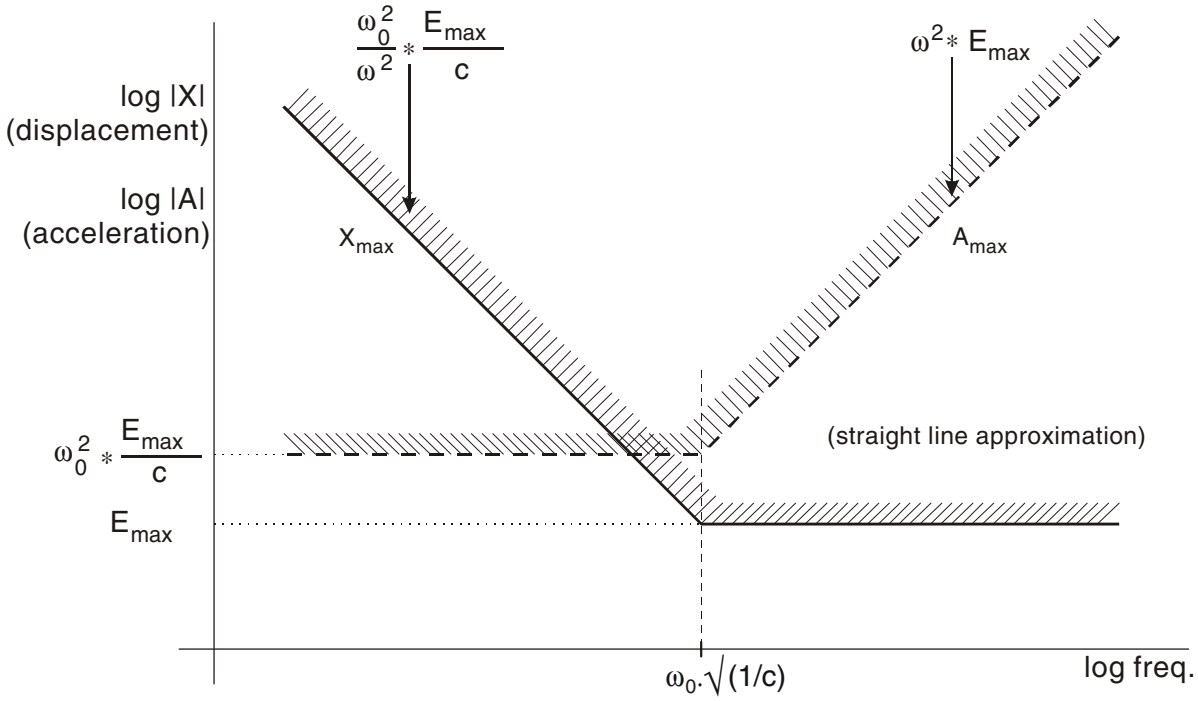
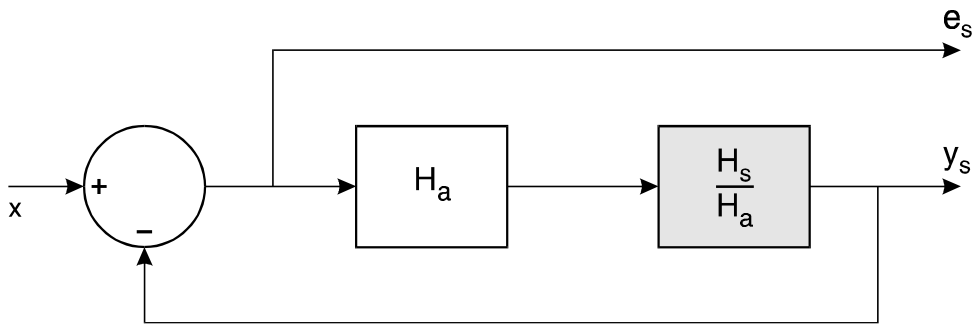
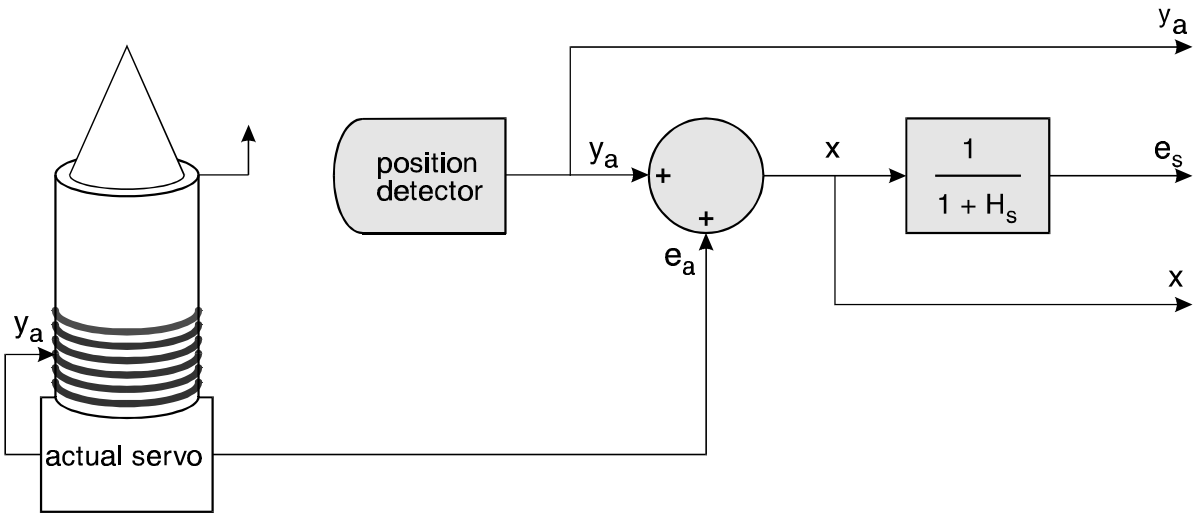
C.12 Max allowed displacement and acceleration when E_{max} is the max allowed tracking error



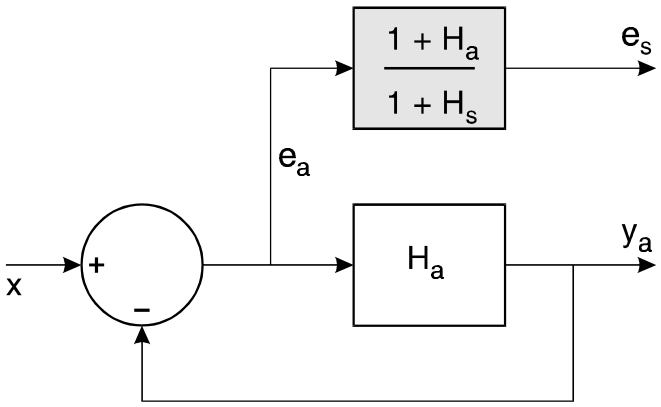
C.13 Conversion of actual servo signals into standard servo signals (1)



C.14 Conversion of actual servo signals into standard servo signals (2)



C.15 Conversion of actual servo signals into standard servo signals (3)



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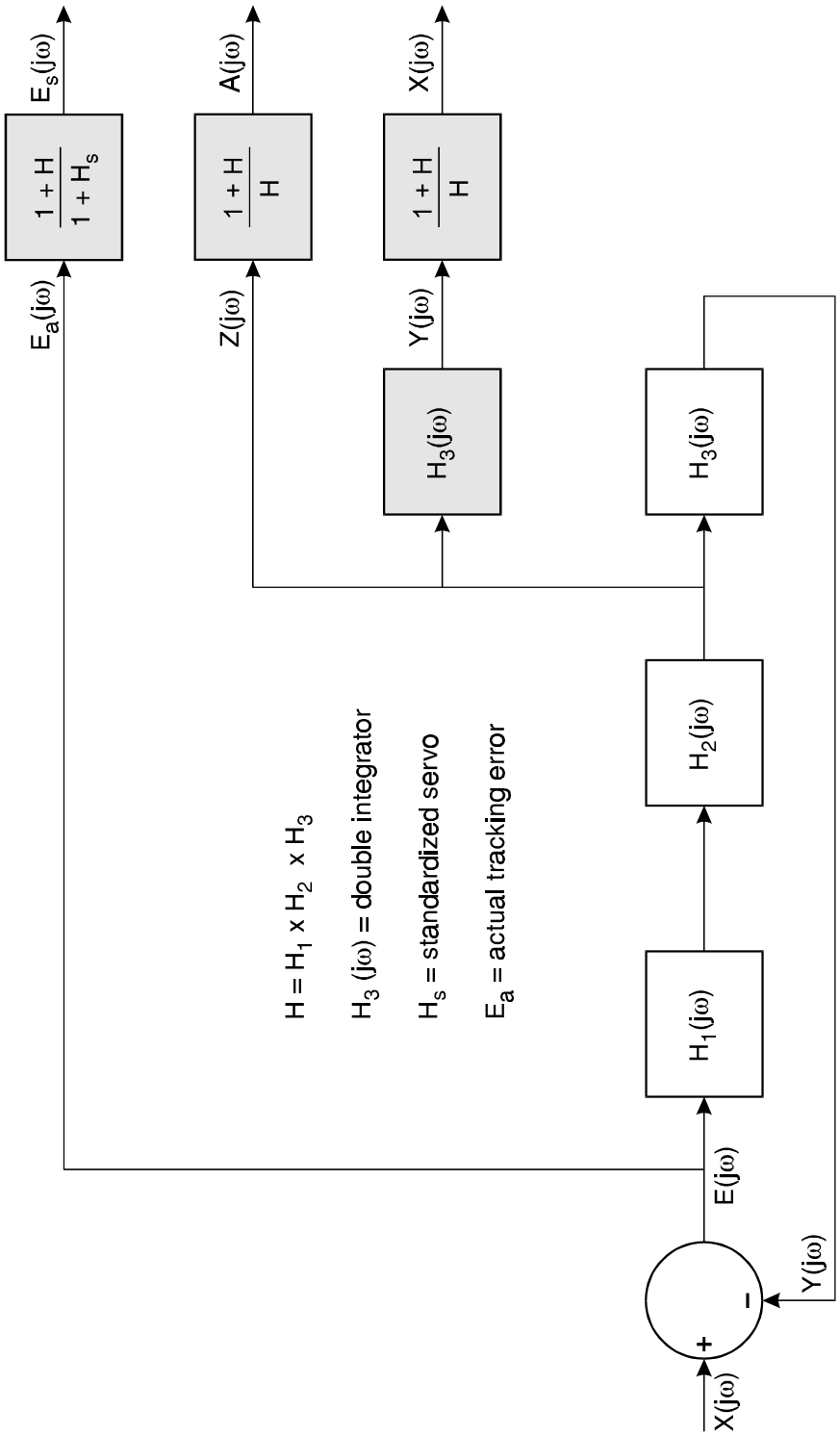
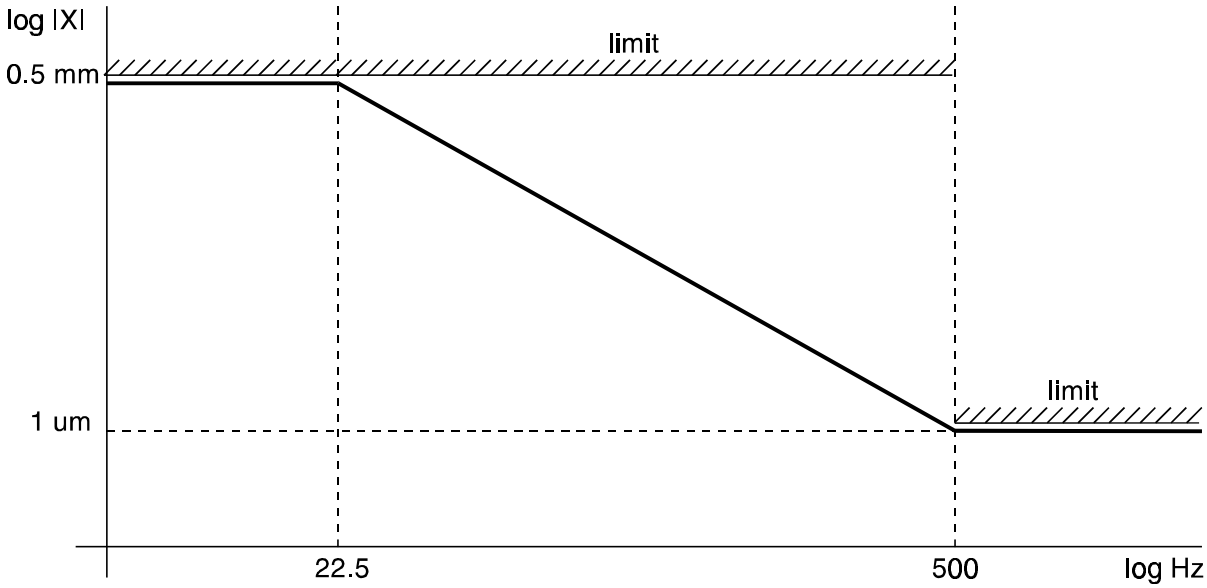
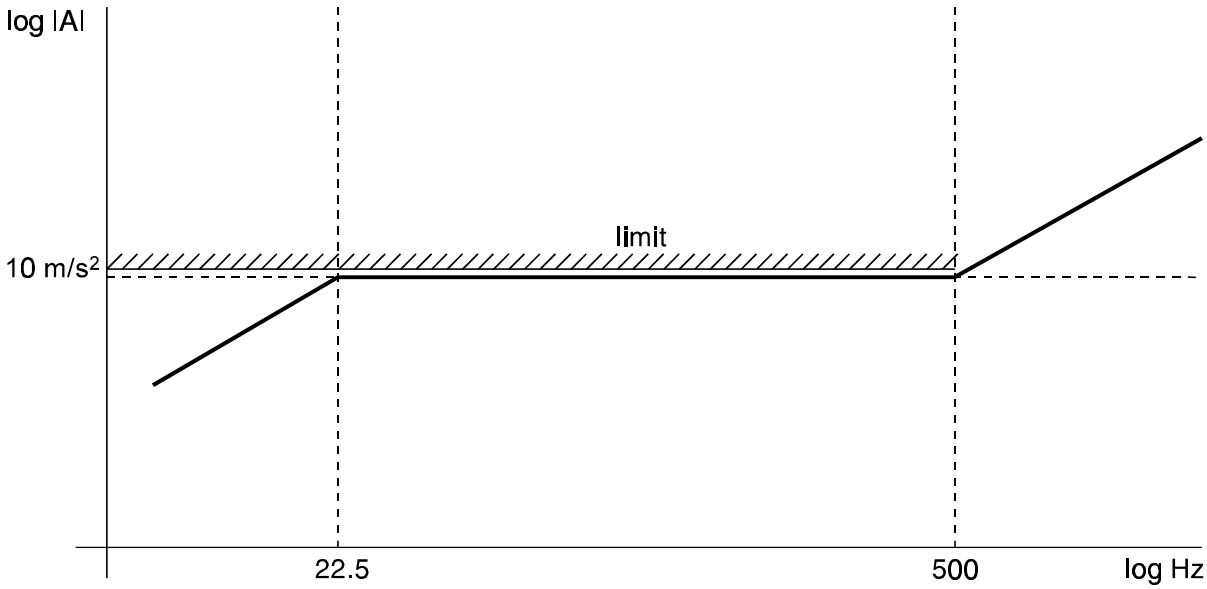
C.16 General block diagram for servo signal retrieval



C.17 Max vertical displacement and acceleration as specified in the Red Book





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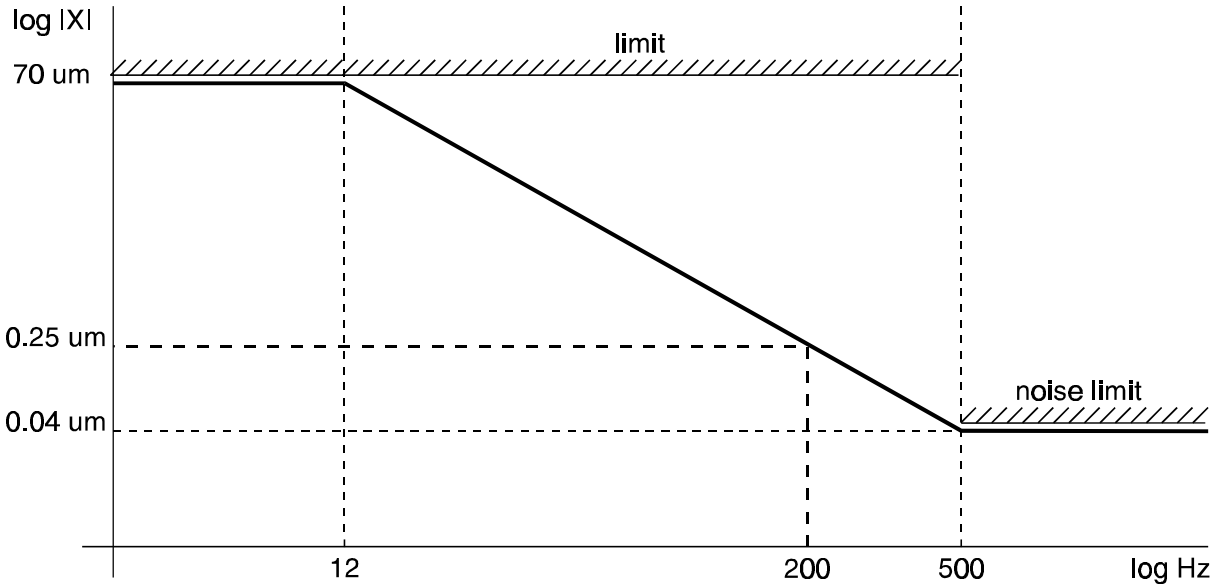
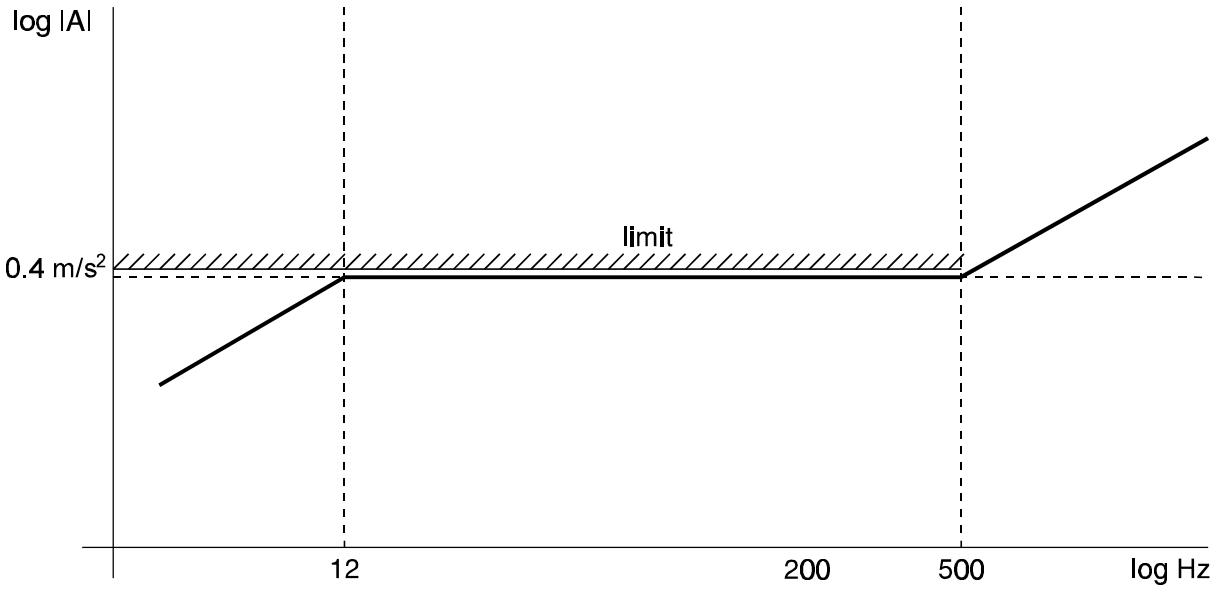
C.18 Max radial displacement and acceleration as specified in the Red Book





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Annex D List of changes

page	chapter	version 1.1	version 1.0
41	6.4.1.2	disc linear velocity: 1.2 m/sec	disc linear velocity: ≤ 1x CD
41	6.4.1.2	electrical filtering: low-pass filter with -3 dB cut-off frequency 20 Hz (first order integrator with timeconstant 8 msec)	electrical filtering: TBD
41	6.4.1.2	Birefringence can show locally big variations. To guarantee sufficient radial resolution it is recommended to keep the step size in radial direction ≤ 0.25 mm.	---
65	C.12	$\omega_0 \cdot \sqrt{(1/c)}$	f_0

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